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Phytoremediation of PCB Contaminated Soil: Effectiveness and Regulatory Policy

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Phytoremediation of PCB Contaminated Soil: Effectiveness and Regulatory Policy

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science for Environmental Studies at Virginia Commonwealth University.

By

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VCU M.S. Environmental Studies 2011
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Biography

Nathan Pinsker received a B.S. in Biology with a concentration in Environmental Studies from James Madison University in 2009. Since beginning graduate school at Virginia Commonwealth University, he has worked as a graduate teaching assistant and a research assistant for Environmental Stewardship Concepts, LLC. Nathan hopes to work in the field of remediation in order to restore sites back to their natural state for all to enjoy. He hopes that cost effective treatments to ubiquitous pollutants such as PCBs will encourage continuous depletion of PCBs from soil and remove as much risk as possible for the public.

Acknowledgements

Thank you VCU for giving me the opportunity to further my education in the field of Environmental Studies. I would also like to thank Dr. Peter deFur, Dr. Tim Kelly, and Dr. Edward Crawford for being a part of my committee for helping me get through the process of entering the M.S. program and assistance in critiquing the paper. Big thanks to Dr. deFur for encouraging the idea and his continuous support throughout my graduate career. I would also like to thank Donna McClish and Matt from VCU's stat consulting for their help with my statistics. Thank you Dr. Michael Blaylock of Edenspace for meeting with me to helping get organized to start my paper and discussing issues I may run into and what will be important to look into.

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Acronyms

AFCEE- Air Force Center for Environmental Excellence
AMF- Arbuscular Mycorrhizal Fungi
ANCOVA- Analysis of Covariance
ARAR- Applicable or relevant and appropriate requirements
BAF- Bioaccumulation Factors
BDAT- Best Demonstrated Available Technology
CDF- Closed Disposal Facility
CERCLA- Comprehensive Environmental Response, Compensation, and Liability Act
CAA- Clean Air Act
CFR- Code of Federal Regulations
CWA- Clean Water Act
DHHS- Department of Health and Human Services
ED- Endocrine Disruptors
EDTA- Ethylenediamine Tetra-acetic Acid
FS- Feasibility Study
GHG- Greenhouse Gases
IARC- International Agency for Research on Cancer
ISTD- In-Situ Thermal Desorption
LMWAO- Low Molecular Weight Antioxidants
LTM- Long-term Management
MCL- Maximum Contaminant Level
MNR- Monitored Natural Recovery
NCP- National Contingency Plan
NPL- National Priority List
PAH- Polycyclic Aromatic Hydrocarbons
POP- Persistent Organic Pollutants
PCB- Polychlorinated Biphenyls
PCE- Tetrachloroethylene
PRG- Preliminary Remediation Goals
RAMED- Randomly Methylated-β-Cyclodextrins
RCRA- Resource Conservation and Recovery Act
RI- Remedial Investigation
ROD- Record of Decision
SARA- Superfund Amendments and Reauthorization Act
SITE- Superfund Innovative Technology Evaluation
SWDA- Safe Water Drinking Act
TCE- Trichloroethene
TNT- Trinitrotoluene
TSCA- Toxic Substances Control Act
U.S. EPA- United States Environmental Protection Agency

Common and Scientific Names of Plants

Crops

Horseradish (*Armoracia rusticana* G.G, B.M, S)
Rice (*Oryza sativa* L.)
Tobacco (*Nicotiana tabacum* L.)

Cucurbits

Cucumber (*Cucumis sativus* L. *cv Marketmore*)
Pumpkin (*Cucurbita pepo* L. *cv Howden*)
Squash (*Cucurbita pepo* L. *cv Goldrush*)
Summer Squash (*Cucurbita pepo* L. *ssp ovifera cv Zephyr*)
Zucchini (*Cucurbita pepo* L. *cv Senator hybrid*)
Zucchini (*Cucurbita pepo* L. *cv Black Beauty*)

Grasses

Barnyard grass (*Echinochloa crus-galli* L.)
Deertongue (*Panicum clandestinum* L.)
Reed canary grass (*Phalaris arundinacea* L.)
Rye grass (*Lolium multiflorum* L.)
Switchgrass (*Panicum virgatum* L.)
Tall fescue (*Festuca arundinacea* Schreb)

Legumes

Alfalfa (*Medicago sativa* L.)
Soybean (*Glycine max* L.)
White lupin (*Lupinus albus* L.)

Sericea lespedeza (*Lespedeza cuneata* G. Don)

Weeds

Black bindweed (*Polygonum convolvulus* L.)
Black medick (*Medicago Lupulina* L.)
Black nightshade (*Solanum nigrum* L.)
Blueweed (*Echium vulgare* L.)
Bull thistle (*Cirsium vulgare* Ten.)
Canada thistle (*Cirsium arvense* L.)
Curly dock (*Rumex crispus* L.)
Daisy (*Chrysanthemum leucanthemum* Lam.)

Goldenrod (*Solidago canadensis* L.)
Hedge mustard (*Sisymbrium officinale* L.)
Ladysthumb (*Polygonum persicaria* L.)
Lamb's quarters (*Chenopodium album* L.)
Mullein (*Verbascum Thapsus* L.)
New England aster (*Symphyotrichum novae-angliae* L.)
Purple loosestrife (*Lythrum salicaria* L.)
Ragweed (*Ambrosia artemisiifolia* L.)
Red clover (*Trifolium pratense* L.)
Sedge (*Carex normalis* Mack.)
Shepherd's purse (*Capsella bursa-pastoris* L.)
Sow thistle (*Sonchus asper* L.)
Tufted vetch (*Vicia cracca* L.)
Wild carrot (*Daucus carota* L.)
Yellow foxtail (*Setaria pumila* Poir.)
Yellow rocket mustard (*Barbarea vulgaris* W.T. Aiton)

Abstract

PHYTOREMEDIATION OF PCB CONTAMINATED SOIL: EFFECTIVENESS AND REGULATORY POLICY

By Nathan Isaac Pinsker, M.S. Environmental Studies

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science for Environmental Studies at Virginia Commonwealth University.

Virginia Commonwealth University, 2011

Major Advisor: Peter L. deFur, PhD Environmental Studies

The purpose of this paper was to combine available peer-reviewed literature on PCB phytoremediation and make direct comparisons using ANCOVA statistics in order to determine if and what plants are presently a viable option for the remediation of PCB contaminated soils. Pumpkin (*Cucurbita pepo* cv Howden) consistently had the top root and shoot concentrations, as well as total plant accumulation. Their consistency shows that they can be reliable in the field and the most viable option. Tall fescue and sedge were also top contenders. Due to the small sample size for many plants and accounting for several confounding variables, very few of plant species and groups showed to be significantly better at PCB accumulation. PCB phytoremediation can be used in conjunction with other technologies or as an early action plan to begin decreasing PCB concentration levels as well as contain the PCBs, thereby preventing any release.

Introduction

Purpose

Research in the field of Polychlorinated biphenyl (PCB) phytoremediation has been growing in the past twenty years in the hopes to be an accepted long-term remedial strategy for PCB contaminated soil throughout the world. Before phytoremediation can be accepted as an alternative strategy, sufficient evidence must demonstrate the effectiveness of phytoremediation in the field. Phytoremediation of toxic metals and radionuclides, including lead, arsenic, copper, zinc, mercury, uranium, strontium, and cesium, have been successfully demonstrated at multiple sites under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA) regulatory oversight, under the U.S. EPA's Superfund Innovative Technology Evaluation (SITE) program, and to accomplish industrial and residential site goals (U.S. EPA, 2000). Literature reviews have compared similar articles, but never has there been a paper that adjusts the data in a way that directly compares plant effectiveness and backs it up with statistics. The variability in testing methods and the way results are depicted makes comparisons difficult, thereby slowing down the development of PCB phytoremediation. This study aims to concentrate available data and compare the effectiveness of different plants to remediate soils based on several criteria such as soil change and bioaccumulation abilities.

Polychlorinated Biphenyl Background

PCBs were once widely used as coolants and lubricants in transformers, capacitors, and other electrical equipment (ATSDR, 2010) because of their thermal stability, chemical inertness, non-flammability, high electrical resistivity, low acute

toxicity (Borja et al., 2005), incombustibility, and low volatility (Rodrigues et al., 2000). PCBs' high chemical stability is the reason for their persistence in the environment and their lipophilicity results in their accumulation in the biota and their concentration in the food chain. PCBs were also used in hydraulics, heat transfer fluids, as plasticizers in paint, and as dye carriers in carbonless copy paper (U.S. EPA, 1993). PCBs were manufactured as industrial mixtures called Aroclors, based on the percentage of chlorine. Aroclor 1260 was comprised of 60% chlorine by weight and contained a number of individual PCB congeners. The composition of PCB mixtures found in the environment differs from the original commercial preparations because the lowest chlorinated congeners are more volatile and easily degradable, which means they have either migrated or been transformed by microorganisms. The higher chlorinated congeners are left behind causing soil to consist of mainly highly chlorinated compounds, which are seen at many long-term contaminated sites (Mackova et al., 2006).

PCBs are synthetic organic compounds with two benzene rings each containing up to five chlorine substituents in the *ortho*, *meta*, or *para* positions (Figure 1), resulting in 209 different congeners (Wiegel and Wu, 2000; Campanella et al., 2002). The commercial formulations display various overall percentages of chlorine and congener distribution. For instance, Aroclor 1242 contains 42% of chlorine with a predominance of congeners bearing three and four chlorine atoms and Aroclor 1260 has 60% chlorine content with a predominance of six and seven chlorinated congeners (Mackova et al., 2006). Toxic congeners carry between five and ten chlorine atoms, mostly in the *para* and *meta* positions (Sylvestre, 1985). However, congeners substituted at the 3, 4-*ortho* positions are considered the most toxic (Albro and Mckinney, 1981; Borja, 2005).

Dioxin-like PCB congeners contain two chlorines in the *para* position, at least two chlorines in the *meta* position, and at most one chlorine in the *ortho* position (Bedard, 2003). This arrangement allows the PCB molecule to rotate and assume a coplanar orientation, causing the dioxin-like behavior (Baars et al., 2004). While dioxin-like PCBs are more carcinogenic, non-coplanar congeners are more disruptive of cognitive function (Faroon et al., 2001).

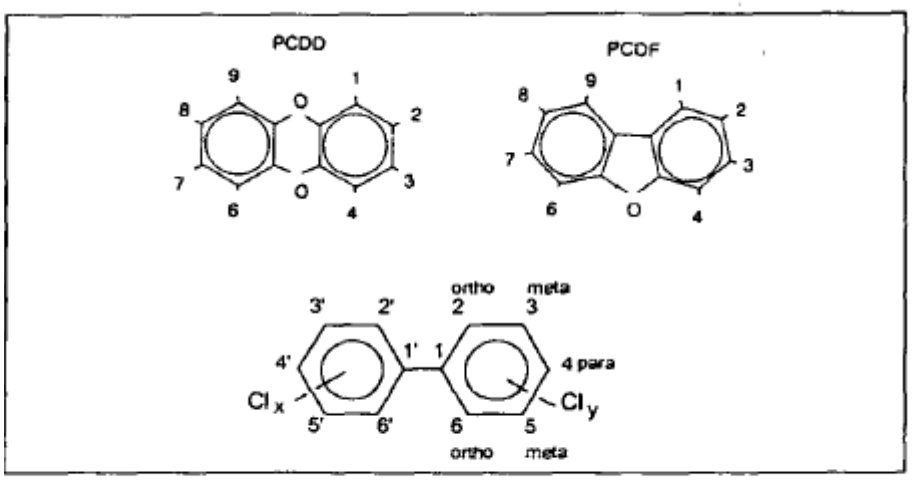


Figure 1. Structural representation of polychlorinated dibenzo-p-dioxin (PCDD), dibenzofurans (PCDF) and biphenyls (PCB) (Campanella et al., 2002).

PCBs are very persistent, hydrophobic, and generally do not migrate. Soil characteristics that affect the mobility of the PCBs include soil density, particle size distribution, moisture content, and permeability (U.S. EPA, 1990). PCBs with fewer chlorine atoms are more soluble, more amenable to chemical and biological degradation, and less persistent in the environment than those with more chlorine atoms (Amend and Lederman, 1992). As of February 2, 2011, 457 sites on the National Priority List (NPL) are contaminated with PCBs (U.S. EPA, 2011a). The number increased by six since October 2010. The cost for traditional remediation worldwide is estimated to be between

$U.S. 25-50 billion annually (Glass, 1999; McGuiness, 2009). New, low-costing remedial techniques are needed in order to decrease the amount of widespread contamination.

The widespread use of PCBs inevitably resulted in their deliberate and unintentional discharges into the environment. From 1929 to 1980, the cumulative world production of PCBs was approximately 2.4 billion pounds (Amend and Lederman, 1992). Thirty-one percent of all PCBs currently reside in the natural environment (Wiegel and Wu, 2000; Holoubek, 2001; Mikszewski, 2004; McGuiness, 2009), four percent has been destroyed, and sixty-five percent is still in use or in storage (Narasimhan et al., 2003). Today, PCBs can be found in soils, sediments, water, plants, fish, wildlife, and human tissues (Jacobson *et al*., 1989; Zeeb et al., 2006).

Health

PCBs are probable human carcinogens according to the Department of Health and Human Services (DHHS), EPA, and the International Agency for Research on Cancer (IARC) (Van Aken et al., 2010). Humans exposed to PCBs have an increased risk of developing cancers like non-Hodgkins lymphoma (Johnson et al., 2000). PCBs also cause non-cancer health effects, such as reduced ability to fight infections, low birth weights, and learning problems (U.S. EPA, 2009). PCBs have been classified as endocrine disruptors (EDs), which are defined as "exogenous agents that interfere with the synthesis, secretion, transport, metabolism, binding, action, or elimination of natural blood born hormones that are present in the body and that are responsible for homeostasis, reproduction, and developmental processes" (Kavlock and Ankley 1996). Adverse health effects include liver damage, skin irritation (chloracne), reproductive dysfunction, and cancer (Rahuman et al., 2000).

Effects of PCBs in animals include changes in the immune system, behavioral alterations, and impaired reproduction. Research has shown that babies born to mothers with high levels of PCB contamination show abnormal behaviors such as problems with motor skills and a decrease in short-term memory (Faroon et al., 2001). Jacobson and Jacobson (1996) found that, "a slightly higher than average intrauterine exposure to PCBs may cause deficient, reduced, or lowered fetal and postnatal growth, retarded psychoneurological development, and reduced cognitive ability."

PCB contaminated soils are cleaned up to concentrations that are set for a specific site or satisfy Preliminary remediation goals (PRGs). PRGs are upper concentration limits for specific chemicals in specific environmental media that are anticipated to protect human health and the environment. PRGs combine current human health toxicity values with standard exposure factors to estimate contaminant concentrations in environmental media (soil, air, and water) that are considered by the Agency to be health protective of human exposures (including sensitive groups), over a lifetime (U.S. EPA, 2011b). PRGs for PCB concentrations in soil are 1 ppm for sites in or expected to be in residential areas and 10 to 25 ppm for sites where non-residential land use is anticipated (U.S. EPA, 1990). A soil PCB concentration of 1 ppm is the starting point for residential scenarios because it reflects a protective, quantifiable concentration for soil that equates to a 10^{-5} excess cancer risk assuming no soil cover or management controls (U.S. EPA, 1990). The range of total PCB concentration in soil at individual sites to reach a risk level of 10^{-6} is 0.12– 0.28 ppm for on-site exposure and 10–2000 ppm for 100 m off-site exposure (Labieniec et al., 1994; Zhou et al., 2004).

To protect public health, it is necessary to not only decrease PCB concentrations, but set up techniques to encourage continuous degradation. The lower the concentration, the less risk involved for the people and wildlife living in the area. In order to remediate most PCB contaminated sites, new, less costly remedial techniques are necessary. Phytoremediation of PCBs is in the testing stage to determine if the use of plants is a plausible remedial alternative. Therefore, this technology is being evaluated in Superfund Innovative Technology Evaluation (SITE) demonstrations, and may also be a technology amenable to contaminant recovery (U.S. EPA, 2000).

Current Regulations

Due to adverse health effects caused by PCBs and their persistence in the environment, the Toxic Substances Control Act (TSCA), enacted on October 11, 1976, banned the manufacture of PCBs after 1978 [Section 6(e)]. The first PCB regulations were in the Code of Federal Regulations, promulgated at 40 CFR Part 761, and were finalized on February 17, 1978. These PCB regulations include requirements specifying disposal methods and labeling procedures, and controlling PCB use (Rahuman et al., 2000). PCBs have been designated as a hazardous substance pursuant to CERCLA of 1980 and as a toxic chemical under Section 313 of Title III of the Superfund Amendments and Reauthorization Act (SARA) of 1986. Section 121(b) of SARA requires the EPA "conduct an assessment of permanent solutions and alternative technologies or resource recovery technologies." Special emphasis was placed on those technologies which could permanently decrease the level of pollutants. Congress further provided for a "program of research, evaluation, testing, development, and demonstration

of alternative or innovative treatment technologies" in section 311(b) of SARA (Timian and Connolly, 1996).

CERCLA instituted the National Contingency Plan (NCP) in order to establish a framework for identification and remediation of the nation's most contaminated and hazardous sites. The national goal of the remedy selection process is to select remedies that are protective of human health and the environment, that maintain protection over time, and that minimize untreated waste (U.S. EPA, 1997). Section 121(d)(2)(A) of CERCLA requires adherence to other Federal and State laws through the identification of and compliance with applicable or relevant and appropriate requirements (ARARs). Overall, the NCP has implemented CERCLA requirements involving the protection of human health and the environment, compliance with ARARs of Federal and State laws, be cost-effective, utilize long-term permanent solutions, have short-term effectiveness, reduce the toxicity, mobility, or volume through treatment, implementable, and attain state and community acceptance (Table 1) (U.S. EPA, 1990; U.S. EPA, 1997).

Table 1. National Contingency Plan Requirements and Criteria.

Threshold Criteria	**Fulfillment Requirements**
Overall Protection of Human Health and the Environment	The remedy provides adequate protection of human health and the environment and describes how risks posed through each exposure pathway are eliminated, reduced, or controlled through treatment, engineering, or institutional controls.
Compliance with ARARs*	The remedy meets ARARs set forth in federal and state environmental laws and/or justifies a waiver from such requirements.
Long-term Effectiveness and Permanence	The expected residual risk and the ability of a remedy to maintain reliable protection of human health and the environment over time once cleanup goals have been met.
Reduction of Toxicity, Mobility, or Volume Through Treatment	The statutory preference for selection of the remedial alternative that employs treatment technologies which permanently and significantly reduces toxicity, mobility, or volume through treatment of the hazardous substance as a principal element.
Short-term Effectiveness	Considers the reliability and effectiveness of any mitigative measures taken during remedy implementation to control short-term risks for the site workers, community, and the environment.

Table 1 Continued. National Contingency Plan Requirements and Criteria.

Threshold Criteria	Fulfillment Requirements
Implementability	The technical and administrative feasibility of a remedy, including the availability of materials and services needed to implement a particular option.
Cost effective	Costs must be reasonable
Support Agency Acceptance	Agencies must agree with the remedy
Community Acceptance	The public must approve of the remedy

*Applicable or relevant and appropriate requirements (ARAR) are used in conjunction with risk-based goals to govern Superfund response activities and to establish cleanup goals.

Federal ARARs for PCB contaminated sites are mainly derived from the Toxic Substances Control Act (TSCA) and the Resource Conservation and Recovery Act (RCRA). Other requirements and regulations are derived from the Clean Water Act (CWA), Safe Water Drinking Act (SWDA), and the Clean Air Act (CAA) (U.S. EPA, 1993). Examples of ARARs include hazardous chemical management, restricted activities at a given location, maximum contaminant levels (MCL), and land disposal requirements.

For 2011, EPA requested $1,293.1 million for the Superfund Program. This amount includes $855.5 million for the Superfund Cleanup programs (Table 2) which maintains steady funding overall to support cleanup at hazardous waste sites that address emergencies (Superfund Emergency Response and Removal) at NPL sites. To increase funds, the EPA is in support of reinstating the Superfund taxes, which expired in 1995, to ensure that parties who benefit from the manufacture or sale of substances commonly found in hazardous waste sites contribute to the cost of cleanup. The Superfund tax began when CERCLA was enacted in 1980. CERCLA created the tax on chemical and petroleum industries and provided broad Federal authority to respond directly to releases of hazardous substances that may endanger public health or the environment. $1.6 billion was collected over five years and the tax went to a trust fund for cleaning up abandoned

or uncontrolled hazardous waste sites. The reinstated Superfund taxes are estimated to generate a revenue level of over $1.3 billion beginning in January 2011 to over $2.5 billion annually by 2020. In addition, the Agency provides funds for Superfund program research, where the President's Budget requests $25 million and 108 total work years to be transferred to Research and Development. Research will enable EPA's Superfund program to accelerate scientifically defensible and cost-effective decisions for cleanup at complex contaminated Superfund sites. The Superfund research program is driven by program office needs to reduce the cost of cleaning up Superfund sites, improve the efficiency of characterizing and remediating sites, and reduce the scientific uncertainties for improved decision-making at Superfund sites (U.S. EPA, 2011c).

Table 2. U.S. EPA 2011 budget breakdown focusing on the Superfund Cleanup section (U.S. EPA, 2011c)

Superfund Resources by Program Area in 2011 Budget

(Dollars in Thousands)

Resources by Program Area

(Dollars in Thousands)

	FY 2009 Actuals	FY 2010 Enacted Budget	FY 2011 President's Budget	Change FY10 Enacted to FY11 PresBud*
Operations and Administration	**$130,294.3**	**$139,181.0**	**$138,307.0**	**-$874.0**
(Rent)	*($45,071.8)*	*($44,300.0)*	*($41,888.0)*	*(-$2,412.0)*
(Utilities)	*($1,837.0)*	*($3,397.0)*	*($3,749.0)*	*($352.0)*
(Security)	*($6,056.1)*	*($8,299.0)*	*($8,412.0)*	*($113.0)*
Research: Human Health and Ecosystems	**$3,776.4**	**$3,404.0**	**$3,350.0**	**-$54.0**
Research: Land Protection	**$19,010.1**	**$21,191.0**	**$19,069.0**	**-$2,122.0**
Research: Sustainability	**$96.0**	**$73.0**	**$0.0**	**-$73.0**
Superfund Cleanup	**$943,460.2**	**$856,080.0**	**$855,461.0**	**-$619.0**
Superfund: Emergency Response and Removal	$224,789.2	$202,330.0	$202,784.0	$454.0
Superfund: EPA Emergency Preparedness	$9,934.8	$9,632.0	$9,776.0	$144.0
Superfund: Federal Facilities	$32,761.5	$32,105.0	$31,543.0	-$562.0
Superfund: Remedial	$669,293.0	$605,138.0	$605,138.0	$0.0
Superfund: Support to Other Federal Agencies	$6,575.0	$6,575.0	$5,920.0	-$655.0
Total, Hazardous Substance Superfund	**$1,385,412.2**	**$1,306,541.0**	**$1,293,060.0**	**-$13,481.0**

* President's Budget

EPA started the *Superfund Green Remediation Strategy* to manage the designs of current plans of Superfund Remedial Program to reduce greenhouse gas (GHG) emissions and other negative environmental effects that might occur during remediation. EPA is working towards cleanup programs that use natural resources and energy efficiently, reduce negative impacts on the environment, minimize or eliminate pollution at its source, and reduce waste to the greatest extent possible (U.S. EPA, 2008). In order to accomplish this goal, EPA is attempting to conserve natural resources, minimize waste generation, and reduce energy consumption, consequently improving environmental performance of Superfund activities while fulfilling the mission to protect human health and the environment. In order to improve current technologies, EPA is focusing on energy, air and atmosphere, water, land and ecosystems, and materials and waste issues. Air pollutants and GHGs from the operation of heavy machinery and transport of vehicles and cargo transport. Excavation often involves degradation of onsite and offsite-ecosystems. Green remediation strategies focus on remedial actions that minimize further harm to the area, protect land resources and ecosystems at or near the site, and return sites to ecological, economic, social, or other uses. Also, site remediation uses significant amounts of raw materials and generates hazardous and non-hazardous wastes, including material and debris, which is often transported offsite (U.S. EPA, 2010).

Current Technologies

Strict policy regulation allows only a few accepted technologies for cleaning-up soil at contaminated Superfund sites. Ex-situ remediation tactics are the main permanent long-term remedial strategies involving soil contaminated with pollutants that do not breakdown or volatilize easily. Once the soil has been removed it is incinerated, disposed

of in a landfill, or washed with a solvent. Other remedial strategies involve containment through capping and monitored natural recovery (MNR) (U.S. EPA, 1993).

Incineration, landfilling, and in-situ thermal desorption (ISTD) are common methods for remediating PCB-contaminated soils, two of which require excavation. When excavating PCB contaminated soil, there is risk of PCBs volatilizing (Rahuman et al., 2000). High temperature incineration is most commonly used for complete destruction of PCBs (Rahuman et al., 2000). Specialized incinerators burn PCB-contaminated soils or sediments at temperatures up to 1200ºC and are required to achieve PCB removal efficiencies of 99.9999 percent (U.S. EPA, 1997). Mass air emissions from the incinerator stack may not be greater than 0.001 g PCB/kg of PCB contaminated material (U.S. EPA, 1990). Even with these standards, some incinerators burning persistent organic pollutants (POPs) (pesticides and PCBs) and other waste are associated with the spread of undestroyed and newly formed POPs (dioxins and furans) into the surrounding environment, contaminating air, soil, vegetation, wildlife and human populations (Costner, 1998; Rahuman et al., 2000). The U.S. EPA has approved high efficiency incinerators to destroy PCBs with concentrations above 50 ppm. In fact, TSCA regulations require waste with over 50 ppm PCBs be either incinerated, disposed of in a hazardous waste landfill, or an equivalent EPA approved alternative (Tchobanoglous et al., 1993). Remedial technologies that have the potential to emit PCBs or other contaminants into the air may be required to employ control measures in accordance with the CAA (U.S. EPA, 1993). Control measures could include bag houses, exhaust stacks, and pressure release devices on treatment tanks. Even with the restrictions on exhaust, there is public opposition to hazardous waste incineration due to the fear of exposure to

toxic emissions. The process of excavating contaminated soil for ex situ treatment can disturb previously stable PCBs, and potentially expose both humans and wildlife. Furthermore, incineration is very expensive, costing up to $2,300 per ton for a fixed PCB incinerator (U.S. EPA, 1997; Mikszewski, 2004).

In-situ thermal desorption (ISTD) uses conductive heating elements to directly transfer heat to environmental media such as soil and has the capability of being used beneath structures. In situ thermal desorption generates no dust or odors, minimizes exposure of personnel to hazardous wastes, and is a low profile, low-noise operation (Vinegar, 1998). Soil types include clay, silt, sand, gravel and more with temperatures reaching up to 1,600º F and averaging around 1,000º F, which is hot enough to volatilize and break down organic contaminants such as PCBs. ISTD has been used successfully for many sites (Table 3) and is able to treat volumes greater than 20,000 cubic yards in six to nine months (U.S. EPA, 2005a). ISTD involves simultaneous application of heat and vacuum to subsurface soils in three parts; 1) application of heat, 2) collection of desorbed contaminants through vapor extraction, and 3) treatment of collected vapors. A common setup uses a vertical array of heaters placed inside wells drilled into the remediation zone. For shallow contamination, heaters are setup horizontally and are referred to as blanket heating. When the soil is heated, adsorbed and liquid-phased contaminants begin to vaporize. PCBs will either oxidize, if enough oxygen is present, or pyrolize before being recovered through vapor extraction wells. The vapors are treated using two methods. One method treats extracts vapor without phase separation and uses a thermal oxidizer to break down organic vapors to primarily carbon dioxide and water. The second method uses a heat exchanger to cool extracted vapors (U.S. EPA, 2005a). Costs average $200 to $600 per cubic yard.

The Centerville Beach Naval facility in Ferndale, CA, decontaminated 1,000 cubic yards contaminated with Aroclor 1254 (0.15-860 ppm) using ISTD. Heater and vapor extraction wells were installed in a zone measuring 40 feet long, 30 feet wide, 15 feet deep, and 6 feet apart from each other. Two sealed vacuum blowers were used in parallel for vapor extraction. Final PCB concentrations were less than one and the total cost of the remediation was approximately $650,000 (Tetra Tech, 2000; U.S. EPA, 2005a).

Table 3. Performance of ISTD at POPs Contaminated Sites (Baker,2004; Heron, 2004; Stegemeier and Vinegar, 2001). Table extracted from U.S. EPA, 2005a.

Site Name	Year	Scale	Contaminant	Concentration			
				Initial	Final	Goal	Units
Former South Glens Falls Dragstrip, Moreau, New York	1996	Full	PCB 1248/1254	5,000 (Max)	< 0.8	2	mg/kg
Tanapag Village, Saipan, NMI	1997 - 1998	Full	PCB 1254/1260	10,000 (Max)	< 1	10	mg/kg
Centerville Beach, Ferndale, CA	1998 - 1999	Full	PCB 1254	860 (Max)	< 0.17	1	mg/kg
			Dioxins and Furans	3.2 (Max)	0.006 [1]	1	ug/kg TCDD
Missouri Electric Works, Cape Girardeau, MO	1997	Pilot	PCB 1260	20,000 (Max)	< 0.033	2	mg/kg
Former Mare Island Naval Shipyard, Vallejo, CA	1997	Pilot	PCB 1254/1260	2,200 (Max)	< 0.033	1	mg/kg
Former Wood Treatment Area, Alhambra, CA	2002 - 2005	Full	Dioxins	18 (Mean)	0.01	1	ug/kg

Note:

Avg	Average concentration
Max	Maximum concentration
mg/kg	Milligrams per kilogram (or parts per million)
NMI	Northern Mariana Islands
ND	Below detection limit
TCDD	Tetrachlorodibenzodioxin equivalents
ug/kg	Micrograms per kilogram (or parts per billion)

There are a few limitations to ISTD. Liquid remaining in the remediation zone limits temperature increases beyond 212º F until the water has boiled off. A continuous source of water could prevent ISTD from working properly (U.S. EPA, 2005a). Therefore dewatering and water control measures are necessary for certain sites. Pilot and full scale applications leave traces of contaminants such as dioxins and furans. Sato et al. (2010) decomposed 48–70% of PCBs, however found that toxic equivalencies (TEQs) in the treated and volatilized samples were 2.8–6.3 times and 8.0–10.5 times as high as the TEQs in the initial samples, respectively, indicating increased toxicity after treatment.

When a cost-effective remediation method does not exist, containment strategies such as capping and MNR are considered. MNR means that no active remediation will take place. MNR relies on nature's biological, chemical, or physical processes to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in environmental media under favorable conditions. MNR processes include biodegradation, dispersion, dilution, sorption, volatilization, and chemical or biological stabilization of contaminants (U.S. EPA, 2008). MNR requires continued sampling to determine if the pollutants will break down or dilute under normal conditions, however the half-life of PCBs in soil ranges from 10 to 100 years (Fellenberg, 2000). Therefore, allowing PCBs to remain in the environment and bioaccumulate up the food chain does not seem reasonable. The Air Force Center for Environmental Excellence (AFCEE) calculated the average cost of long-term monitoring for MNR remediation for groundwater contaminated with hydrocarbon plumes ranging from 0.3-60 acres. The monitoring would require 11 monitoring wells with a cost of around $192,000 over the 30 year period estimated for clean-up (AFCEE, 2011). The addition of engineered source treatment increased the average cost to

$816,000 while reducing the time to clean-up to 15 years (AFCEE, 2011) depending on the pollutant.

Capping is done with soil, clay, or asphalt as a way of containing the PCBs and preventing exposure to people and wildlife. Landfill caps can be applied to waste masses too large for other treatments. For persistent substances, burial in landfills is not a destruction technology; it is only a method of containment. Moreover, capping is a relatively ineffective method of containment. Constituents in buried wastes can and do escape into the surrounding environment, primarily through leaching into groundwater and volatilizing into the air. PCBs are known to escape from landfills by volatilizing into the surrounding air and are known to evaporate more rapidly with increased moisture in soils, sediments and even with increased relative humidity of air (Rahuman et al., 2000). Capping is a temporary solution because there is no guarantee that PCBs will not migrate as a result of species living within the soil, and future development will be restricted due to the re-release that would occur during construction.

Economic comparisons between capping and phytoremediation of Pb-contaminated soil at a 1 ha site have indicated the cost and long-term benefits of phytoremediation. Asphalt capping effectively seals the Pb-contaminated soil to prevent any environmental contact and includes the installation of water drainage and parking curbs. Soil capping is less expensive than asphalt capping and uses a 60-cm thick cap of uncontaminated soil from off-site to cover the area of concern. A simple vegetative cover is established on the soil cap surface to prevent erosion and restrict water infiltration. Soil capping requires annual reseeding and re-mulching of 10% of the site, and four mowings per year (Cunningham and Berti, 2000). Site stabilization with asphalt capping and soil

capping are estimated to be over twice as expensive as phytostabilization at $60,000/ha (Cunningham and Berti, 2000). Soil capping does not eliminate the possibility of environmental contamination (Mikszewski, 2004) and does not guarantee that PCB transport from microbes and species living within the soil will be restricted.

Innovative treatment methods must offer potential for comparable or superior treatment performance or implementability, fewer or lesser adverse impacts, or lower costs in order to be considered. In order for phytoremediation to be selected as a remedy at a CERLCA site, it will be necessary to meet or waive the ARARs identified for the site (U.S. EPA, 2000). The guidance manual indicates that an equivalent level of performance for an alternate method of treatment of PCB-contaminated material is demonstrated if it reduces the level of PCBs to less than 2 ppm measured in the treated residual. PCB concentrations must be reduced to 0.1 - 10 ppm for concentrations up to 100 ppm, and percent reductions of 90 - 99.9% must be achieved for higher concentrations (U.S. EPA, 1989).

Phytoremediation

Phytoremediation has been investigated and is currently being used in the field for a variety of organic and inorganic pollutants. Phytoremediation is the use of plants and its related enzymes to decontaminate soil, groundwater, air, sediments, and surface water (Russel, 2005) by extracting and breaking down contaminants while supporting and using native bacteria. The characteristics of plants allow them to extract, degrade, and stabilize PCBs (Figure 2). There are several benefits to phytoremediation such as control of fugitive dust emissions, reduced noise, fewer health risks for workers, increased biodiversity, and high public approval (Russel, 2005).

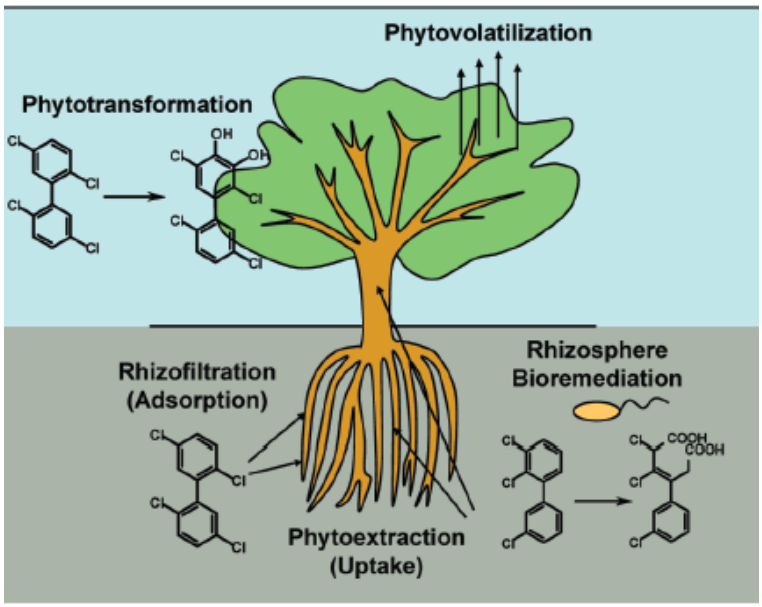


Figure 2. Phytoremediation of PCBs involving several processes: pollutants in soil and groundwater can be taken up inside plant tissues (phytoextraction) or adsorbed to the roots (rhizofiltration; pollutants inside plant tissues can be transformed by plant enzymes (phytotransformation) or can volatilize into the atmosphere by microbes in the root zone (rhizoremediation) (Van Aken et al., 2010).

Clean up of contaminated sites in the U.S. will cost billions of dollars (Chen et al., 2005). Aggressive engineering methods such as excavation are suitable for areas with high concentrations (hot spots), but less-expensive containment and treatment technologies can be used for surrounding areas where contaminated levels are low. The costs for decontaminating a site with phytoremediation can be a fraction of the cost of traditional methods such as excavation followed by incineration or landfilling (Schnoor, 1997; AATDF, 1998; Blaylock et al., 1999; Cunningham and Berti, 2000; Pivetz, 2001). Phytoremediation does not have the destructive impact on soil fertility and structure that some more vigorous conventional technologies may have, such as excavation followed by acid extraction, soil washing, and thermal desorption (Greger and Landberg, 1999).

Remedial action requires years to develop and implement after a site is deemed hazardous. Phytoremediation can be installed and removed as part of a remedy. The interim ecosystem benefits include early removal and degradation of the pollutants (U.S.

EPA, 2000). Established rooted vegetation has the ability to stabilize soil thereby preventing wind erosion and adsorption of contaminants to soil that transports into water streams (Macek et al., 2004). Wind blown dust is an important exposure pathway for humans and animals living within the vicinity of a hazardous waste site. Depending on the site, phytoremediation can be used alone or in conjunction with other remediation methods to help decrease the amount of contaminated dust in the air. Phytoremediation is most suitable for remediating sites or portions of sites with widespread, low-mid level contaminants that are often too expensive to remediate by traditional means.

Phytoremediation has already been accepted by EPA to clean up a variety of pollutants. Organic pollutants such as petroleum hydrocarbons, gas condensates, crude oil, chlorinated compounds, pesticides, and explosive compounds have been shown to successfully be remediated using phytotechnologies (ITRC, 2009). Phytoremediation has been used at Superfund sites to clean soil and groundwater contaminated with several different types of pollutants such as trinitrotoluene (TNT), trichloroethene **(**TCE), tetrachloroethylene **(**PCE), pesticides, polycyclic aromatic hydrocarbons **(**PAH), metals, cesium and mercury (Table 4) (U.S. EPA, 2000).

Table 4. Phytoremediation at Superfund Sites (U.S. EPA, 2000)

Site Name, State	Date Planted	Plant	Contaminant/Matrix
Carswell Site, TX	Spring 1996	Eastern cottonwood tree	TCE/groundwater at 4-12 feet
Aberdeen Proving Grounds, MD	Spring 1996	Hybrid poplar trees	TCE/groundwater
Edward Sears Site, NJ	Fall 1996	Hybrid poplar trees	TCE/groundwater at 8 feet
Iowa Army Ammunition Depot, IA	Spring 1997	Wetland and terrestrial plants	TNT/soil and pond water
Fort Wainwright, AK	Spring 1997	Felt leaf willow	Pesticides/soil and groundwater
Kaufman & Minteer, NJ	Spring 1997	Hybrid poplar trees	PCE/groundwater
Calhoun Park, SC	Fall 1998	Local landscaping plants	PAH/groundwater at 1-4 feet
Solvent Recovery Systems of New England, CT	Spring 1998	Hybrid poplar trees	Mixed solvents/groundwater
Twin Cities Army Ammunition Plant, MN	Spring 1998	Corn, Indian mustard	Metals/soil
Bofors-Nobel, MI	Planting scheduled	Various trees and wetland plants	Residual sludge in waste lagoons
Del Monte, HI	Spring 1998	Koa haole	Pesticides/soil and groundwater
INEEL, ID	Spring 1999	Kochia, willow	Cesium, mercury in soil

The costs of phytoremediation include preliminary treatability studies to select the proper plant, soil preparation, planting, maintenance, sampling, and disposal. Maintenance may include irrigating, watering, removing invasive plants, pruning (Ficko et al., 2010), and fertilizing (Pivetz, 2001). A field-scale research study of rhizodegradation of petroleum hydrocarbons in soil cost around $240/yd^3 or $160/ton, and the cost for a full-scale system were estimated to be significantly lower, at $20/yd^3 or $13/ton. The cost difference is due to economy of scale and lack of research-oriented expenses (AATDF, 1998; Pivetz, 2001).

Based on a small-scale field application of lead phytoextraction, predicted costs for removal of lead (Pb) from surface soils using phytoextraction were 50% to 75% of traditional remedial technology costs (Blaylock et al., 1999). The cost for decontaminating a 1-ha Pb-contaminated site at a depth of 30 cm is estimated to be $279,000 using phytoextraction, where solidification with off-site stabilization and soil washing cost $1,600,000 and $790,000 respectively (Table 5; Cunningham and Berti, 2000). The phytoextraction is based on ten years with three harvests a year with the harvested biomass being disposed in a hazardous waste landfill at 40 tons/ha. The cost of phytoextraction is much less than the engineering techniques for decontamination and the cost are spread out over 10 years, requiring less money up front (Cunningham and Berti, 2000). The cost for phytoremediation of 60-cm deep lead-contaminated soil was estimated at $6/m^2 (in 1996 dollars), compared to the range of about $15/m^2 for a soil cap to $730/m^2 for excavation, stabilization, and off-site disposal (Berti and Cunningham, 1997; Pivetz, 2001). Schnoor (1997) compares the costs of soil fixation, landfilling in RCRA approved hazardous waste site, soil extraction, and phytoextraction for metals

(Table 6). Phytoextraction costs considerably less than the other conventional methods. PCBs have different properties and will accumulate and degrade differently than metals, but the costs for incineration and landfilling will be similar. The phytoextraction cost is based on planting for 18 to 60 months (Schnoor, 1997). The preliminary treatability studies should be designed to ensure contaminant concentrations will reach target levels in the designated time. If target levels are not met, there is still a good chance that continuing with phytoremediation will still be cost efficient compared to extraction.

Table 5. Estimated Economic Analysis of Remediation Alternatives for a 1-ha Pb-Contaminated Site (Cunningham and Berti, 2000)

Alternative	Clearing	Excavation to 30 cm	Soil Disposal	Variable Costs		Net Present Cost
				First Year	10 y Recurring[a]	
				(US$)		
Site Decontamination						
Solidification and stabilization off-site[b,e]	8800	43,000	1,300,000	270,000	0	1,600,000
Soil washing[c,e]	8800	43,000	290,000	450,000	0	790,000
Phytoextraction	8800	0	0	0	270,000	279,000
Site Stabilization						
Asphalt capping[d,e] (parking lot)	8800	0	0	150,000	0	160,000
Soil capping[d,e]	8800	0	0	125,000	6700	130,000
Phytostabilization	8800	0	0	44,000	6700	60,000

[a] Costs include a 12% annual discount rate and 3% annual inflation rate.
[b] Estimates for solidification and stabilization off-site assumes a landfilling cost of $226 per metric ton of soil; costs are for a regular landfill.
[c] Estimate for soil washing assumes a landfilling cost of $250 per metric ton of soil; costs are for a hazardous waste landfill.
[d] Racer/ENVEST™ Delta Technologies Group Inc., Denver, CO, 1996.[44]
[e] Gary Quinton, DuPont Corporate Remediation Group, personal communication.

Table 6. Cost Advantage of Phytoextraction for Metals (Schnoor, 1997)

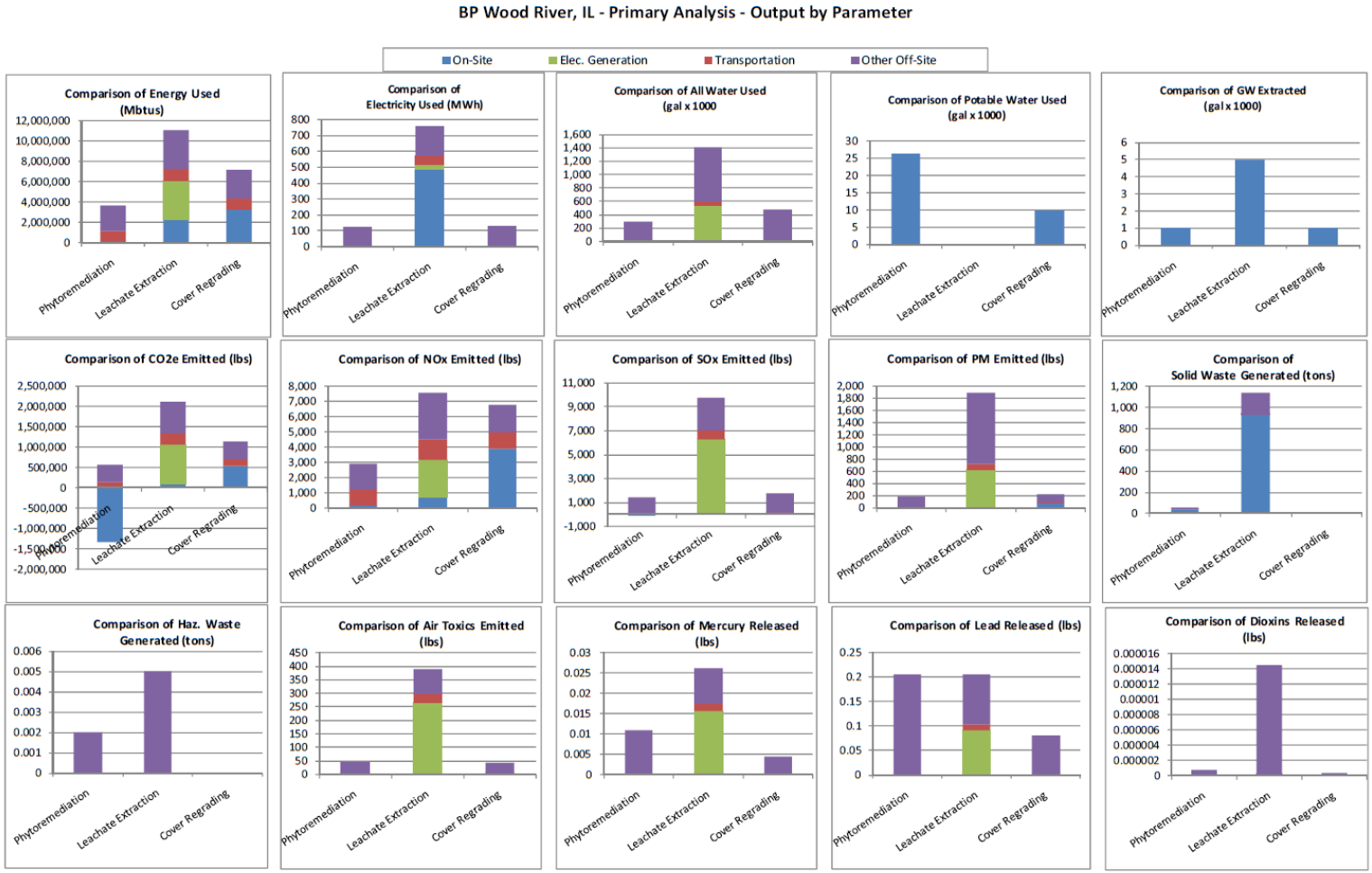
Table 5
Cost Advantage of Phytoextraction for Metals
(Phytotech Technical Summary, 1997)

Type of Treatment	Cost/m^3 ($)	Time Required (months)	Additional factors/ expense	Saftety Issues
Fixation	90-200	6-9	Transport/excavation Long-term monitoring	Leaching
Landfilling	100-400	6-9	Long-term monitoring	Leaching
Soil extraction, leaching	250-500	8-12	5,000 m^3 minimum Chemical recycle	Residue disposal
Phytoextraction	15-40	18-60	Time/land commitment	Residue disposal

Edenspace used a fern, *Pteris vittata,* to phytoextract arsenic from soil as a substitute to excavation. Recently, the ferns were used to clean-up neighborhood yards in Spring Valley, Washington D.C. contaminated with formerly used World War I (WWI) weapons, resulting in high arsenic concentrations. Depending on the extent of contamination, residents were given the option of phytoremediation or excavation. The cost of a single 20' X 20' grid was calculated to be approximately $6,000 and included site preparation, purchase of ferns, monitoring of grids, harvesting of plants, arsenic analysis of soil and fern plants, and grid restoration (Teeter et al., 2004). The approximate cost of excavation and disposal of arsenic contaminated soil was three times that amount, or about $18,000 per grid. The activities of plot preparation, planting, growth and harvest were conducted with minimal disruption to existing trees and perennial vegetation and with no further action required at seven of the eleven properties. To restore the plots, only sod and mulch were needed to restore lawn and garden areas to their previous appearance.

A study done at a disposal unit at the BP Wood River, located Wood River, Illinois, referred to as the Confined Disposal Facility (CDF), to quantify the environmental footprints of three remedial options for managing leachate levels; phytoremediation, leachate extraction, and cover regarding. Trees were to enhance evapotranspiration within the boundary of the CDF. Extraction wells were set up to process leachate and separate oil and water before discharging into the local sanitary sewer. Five acres of the CDF cap were restructured with clay to reduce infiltration. The site was a 26-acre disposal site located on riverfront property on the east bank of the Mississippi River that was used to manage various petroleum and additive wastes. The study measured emissions of various environmental parameters, such as greenhouse gases, criteria pollutants, and air toxics, and the resources used, such as energy and water (Figure 3) (GeoTrans, Inc., 2010). Phytoremediation had considerably lower levels of air pollutants, energy use, and GHGs.

Figure 3. BP Wood River, IL; Comparisons of air pollutants, GHGs, water usage, and energy use between phytoremediation, leachate extraction, and cover regarding (GeoTrans, Inc., 2010).



Degradation

The majority of PCB biodegration occurs in the vicinity of plant roots, known as the rhizosphere, because plant roots are able to assist microbes in the degradation process by supplying nutrients and different types of secondary plant metabolites. Degradation in the rhizosphere increases due to additional oxygen transferred from the root system into the soil, causing enhanced aerobic mineralization of organics and stimulation of co-metabolic transformation of chemicals (Anderson et al., 1993). Plant roots increase soil aeration and moderate soil moisture, which makes favorable conditions for biodegradation by indigenous microorganisms (U.S. EPA, 2000).

Plants have the ability to produce over 100,000 low molecular mass secondary metabolites and some estimates exceed 500,000 (Hadacek, 2002).The exudates cause rhizosphere-inhabiting microbial populations to increase well beyond those of the bulk soil, attracting motile bacteria and fungal hyphae that stimulate an array of positive, neutral or negative interactions with plants (Singer et al., 2003). Plant roots release carbohydrates, enzymes, amino acids, phenolic compounds (Javorska, 2009), flavanoids, terpenes, coumarins, and resin acids that microbes can utilize (Singer et al., 2003; U.S. EPA, 2005b) as a substrate for PCB oxidation rather than biphenyl (Focht, 1995). A synergistic action of both rhizosphere microorganisms and plants can lead to increased availability of hydrophobic compounds affecting their removal and/or degradation (Leigh et al., 2004; Mackova, 2007). PCB degradation abilities have previously been observed in gram-negative strains belonging to the genera *Pseudomonas, Alcaligenes, Achromobacter, Burkholderia, Acinetobacter, Comamonas, Sphingomonas, and*

Ralstonia, and gram-positive strains belonging to the genera *Arthrobacter*, *Corynebacterium, Rhodococcus,* and *Bacillus* (Sakai, 2005).

Plant phenolics and flavonoids have been demonstrated to support the growth and degradation activities of the PCB-degrading bacterium *Rhodococcus* sp. strain MB1 in culture (Donnelly et al., 1994; Yu et al., 2000; Leigh, 2006). Nontoxic plant inducers such as terpene are rich in plant residues and composts containing orange skin and pine needles. These inducers have shown to increase the numbers of PCB degraders (Dzantor and Woolston, 2001), including *Rhodococcus* species (Hernandez et al., 1997) and *Pseudomonas pseudoalcaligenes* KF107 by 10-100 fold increase compared to soil samples without inducers (Oh et al., 2003). *Rhodococci* appears to be well adapted for PCB rhizoremediation because it is able to utilize plant secondary compounds and degrade PCBs. Specifically, *Rhodococcus* sp. Strain RHA1 (Masai et al., 1997) has the ability to cleave lesser chlorinated biphenyl rings to yield chlorinated benzoates and pentanoic acid derivatives which are often degradable by other bacteria (McGuiness, 2009). Leigh et al. (2006) found culturable PCB degraders throughout a PCB contaminated site in South Moravia, Czech Republic alone and in association with plants. These plants were predominantly *Rhodococci,* and the degradation abilities exhibited by isolates revealed that the indigenous microbial community had strong catabolic potential for PCB degradation. The carboxyl groups from plant released acids chelate soil-borne cations, resulting in increases of nutrient and pollutant availability (Whitefield et al, 2007). Phenylpropanoid-utilizing microbes are more competitive and are able to grow at least 100-fold better than their auxotrophic mutants on roots of plants that are able to synthesize or overproduce phenylpropanoids, mainly flavonoids (Narasimhan et al.,

2003). As a result, plants have shown to significantly decrease lower chlorinated biphenyls (Tetra-Cl, Penta-Cl), but also induced significant depletion of the high chlorinated biphenyls (N=Hexa-Cl) in the soil (Luo et al., 2008; Xu et al., 2010).

Pathway

Microorganisms participate in biodegradation by producing enzymes that modify the organic pollutant into simpler compounds through one of two forms, mineralization or co-metabolism. In mineralization, organisms use the organic pollutant as a source of carbon and energy resulting in the reduction of the pollutant to its constituent elements. Co-metabolism requires a second substance as a source of carbon and energy for the microorganisms but the target pollutant is transformed at the same time. Products of the co-metabolized PCBs can be further broken down by mineralization (Borja et al., 2005). Depending on the level of chlorination, microbial degradation of PCBs will occur through two major microbial metabolic pathways, anaerobic and aerobic and last a minimum period of two years (Campanella et al., 2002). The pathway is dependent on the degree of chlorination, redox conditions, temperature (Figure 4), pH, presence of toxic or inhibitory substance and competing substrates, microorganism involved (Figure 5), availability of suitable electron acceptors, and interactions among microorganisms. All these factors interplay and make the rates of biodegradation unpredictable (Borja et al., 2005).

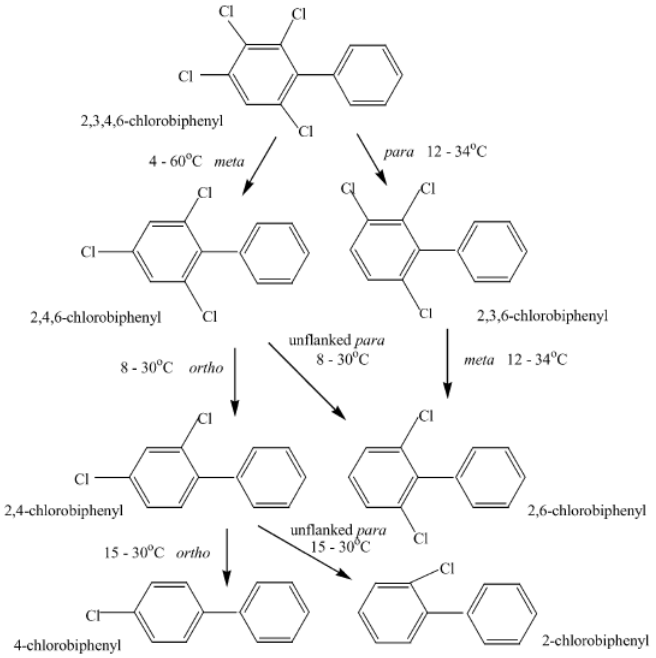


Figure 4. Temperature dependent routes for anaerobic microbial reductive dechlorination (Wiegal and Wu, 2000; Borja, 2005)

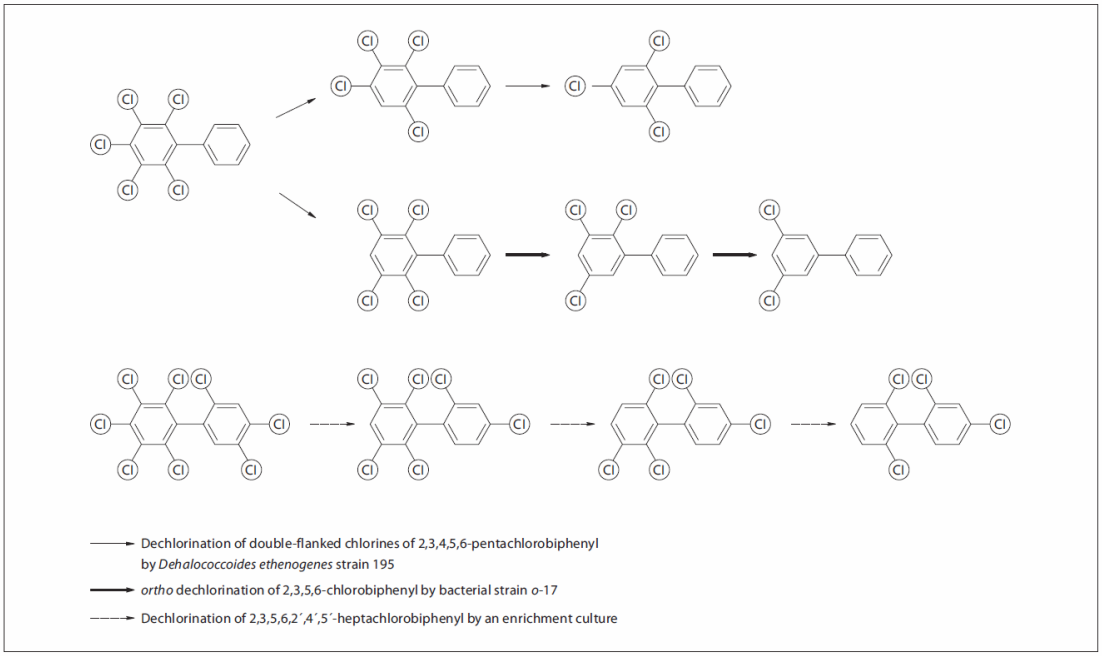


Figure 5. Bacterial reductive dehalogenation of PCBs by related bacteria (Bedard et al., 2006; Cutter et al., 2001; Fennell et al., 2004; Pieper and Seeger, 2008).

Anaerobic dechlorination generally occurs for PCB congeners with four or more chlorine atoms that undergoes anaerobic reductive dechlorination. An anaerobic reductive

dechlorination requires energy in order for PCBs to serve as electron acceptors for the oxidation of organic carbon (Van Aken et al., 2010). Electron acceptors are generally the factors limiting metabolism in anaerobic environments and therefore microorganisms that could use PCBs as terminal electron acceptors would be at a selective advantage (Brown et al., 1987; Borja et al., 2005). Degradation begins with microbial reductive dechlorination of PCBs by removing the *meta* and *para* chlorines from highly chlorinated congeners (Wiegel and Wu, 2000) and leaving lesser-chlorinated *ortho*-substituted congeners (Figure 6) (Olson et al., 2003). Microorganisms that reductively dechlorinate PCBs are widespread in contaminated areas and involve species related to *Dehalococcoides* (Abraham et al., 2002; Bedard et al., 2006). Sequencing the genome of *Dehalococcoides ethenogenes* 195, a well-characterized tetrachlorethene degrader, revealed the presence of several reductive dehalogenase genes potentially implicated in PCB transformation (Pieper and Seeger, 2008).

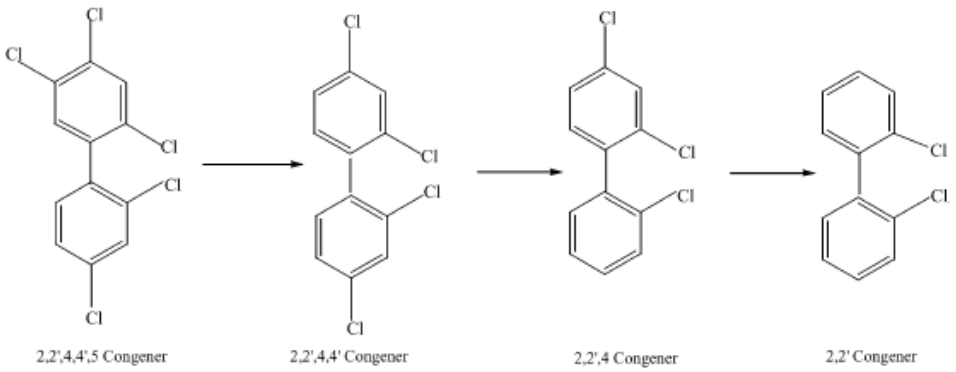


Figure 6. Potential pathway for anaerobic dechlorination of a highly chlorinated congener (Fish and Prinicipe, 1994; Borja et al., 2005).

Congeners with 1 to 6 chlorine atoms can be oxidized by aerobic bacteria (Campanella et al., 2002). Aerobic oxidative biodegradation of PCBs typically involves two clusters of genes. The first cluster is responsible for transforming PCBs into chlorbenzoic acid, chlorobenzoates and chlorinated aliphatic acids (*biphenyl upper*

pathway), and the second one is for further mineralization of chlorobenzoates and aliphatic acids (*biphenyl lower pathway*) (Borja et al., 2005; Pieper and Seeger, 2008; Furukawa and Fukihara, 2008; Van Aken et al., 2010) into carbon dioxide, water, and chloride (Demnerova et al., 2003). The lower chlorinated PCB congeners undergo co-metabolic aerobic oxidation mediated by dioxygenases, which results in a ring-opening and potentially complete mineralization of the molecule (Figure 7) (Borja et al., 2005; Furukawa and Fukihara, 2008; Vasilyeva and Strijakova, 2007; Van Aken et al., 2010).

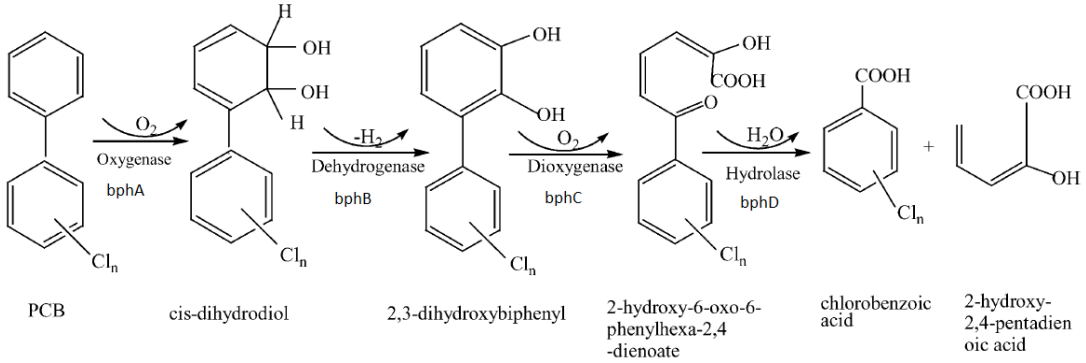


Figure 7. Major steps in the conversion of PCBs into chlorobenzoates (Sylvesre and Sandossi, 1994; Borja et al., 2005; Van Aken et al., 2010).

Specifically, aerobic degradation begins when the biphenyl dioxygenase, a multi-component enzyme constituted by an iron-sulfur protein (ISP_{bph}), interacts directly with the substrate to introduce two oxygen atoms on adjacent positions on the biphenyl ring. Electrons are then transferred from NADH to ISP_{bph} by the two other components of the dioxygenase, a ferredoxine and a reductase (Mackova et al., 2003). The biphenyl dioxygenase components are encoded by four genes clustered in a single operon in most of the strains: *bphA*, *bphE*, *bphF*, and *bphG* (Figure 7). A multicomponent dioxygenase (*bph*A) initiates hydroxylation of two adjacent biphenyl carbons to form an arene *cis*-diol

(Van Aken et al., 2010) or *cis*-(2R, 3S)-dihydroxy-1-phenylcyclohexa-4,6-diene (Mackova et al., 2003). A dehydrogenase (encoded by *bphB* gene) further transforms the first metabolite to a dihydroxybiphenyl that is transformed by a second dioxygenase (encoded by *bphC* gene) in an open-ring compound. The fourth step of the upper pathway involves a hydrolase (*bph*D) that cleaves the resulting molecule into chlorobenzoate and 2-hydroxypenta-2, 4- dienoate (Van Aken et al., 2010) or forms a benzoic acid (Mackova et al., 2003). The mineralization of benzoic acids is performed by another group of enzymes constituting the lower pathway (Mackova et al., 2006). *Burkholderia xenovorans* LB400 is the most potent natural occurring strain and has the ability to degrade most congeners containing three chlorine atoms and some containing four or five.

Phytoextraction

The most efficient technique of phytoremediation is phytoextraction, the act of contaminants being transported from the soil and into the plant for storage (Cherian and Oliveira, 2005). Once plants have accumulated the greatest amount of PCBs possible, they can be harvested and either incinerated or placed in a RCRA approved hazardous waste site (Macek et al., 2000) depending on the final concentration. If the plants have a concentration less than 50 ppm, they may be disposed of in a municipal waste landfill or something of equivalence. The effectiveness of a typical phytoextraction project is judged by the decrease in soil concentration of the target constituent, per unit time. This rate is a function of the plant biomass production per unit area per crop rotation, average concentration of the constituent in the plants, and number of crops (Teeter et al., 2004a). Root uptake of organic compounds from soil is affected by physicochemical properties of

the compounds, environmental conditions, soil characteristics, organic matter content, pH, moisture, and plant characteristics (Cunningham et al., 1997). The passive processes of root uptake (Schwarz and Jones, 1997) cause organic contaminants to diffuse into free spaces in the endodermis of the root. The contaminant molecules then bypass the casparian strip, where they can be translocated up the shoots via the vascular tissue (Zeeb et al., 2006). PCBs are typically adsorbed by the roots and do not readily transpire due to their hydrophobicity (Schnoor et al., 1995; Shaw and Burns, 2003). Highly chlorinated PCB congeners are less mobile within the plant and are adsorbed to the hydrophobic components in the lower portion of the stem (Campanella et al., 2002; Whitfield Aslund, 2007).

Plant peroxidases, both endogenous and exogenous, have the ability to transform PCBs (Mackova et al., 2006). In plants, peroxidases perform antioxidant and certain other functions, including transformation and mineralization of xenobiotics. Plant peroxidases can degrade many PCB congeners (particularly mono-, di-, and tri-chlorobiphenyls) and chlorobenzoic acids (Vasilyeva, 2007). Plant metabolism of PCBs occurs in a three phase process known as the *green liver* model (Figure 8) (Sandermann, 1994). Phase I, the initial activation, consists of oxidation of PCBs to produce various hydroxylated products, characterized by a higher solubility and reactivity. Phase II involves conjugation of phase I-activated compounds with molecules of plant origin forming adducts less toxic and more soluble than parent PCBs. Phase III involves sequestration of the conjugates in plant organelles or incorporation into plant structures like the cell wall (Sandermann, 1994; Van Aken et al., 2010). Black nightshade hairy root cultures exposed to different PCB congeners (di- to penta-chlorinated) resulted in the formation of

hydroxylated PCB metabolites, dichloro and trichlorobiphenyl congeners, while tetrachloro- and pentachlorobiphenyl congeners were not metabolized (Rezek et al., 2007). Black nightshade and tobacco have also shown to degrade mono- and diCB (1–2 mg/l) in a medium with purified peroxidases of PCB in the presence of 0.02% H_2O_2. The metabolites included chlorobenzoic acids, mono-, di-, and trihydroxy derivatives of PCB, and less and more chlorinated PCB congeners (Mackova et al., 2006; Vasilyeva, 2007).

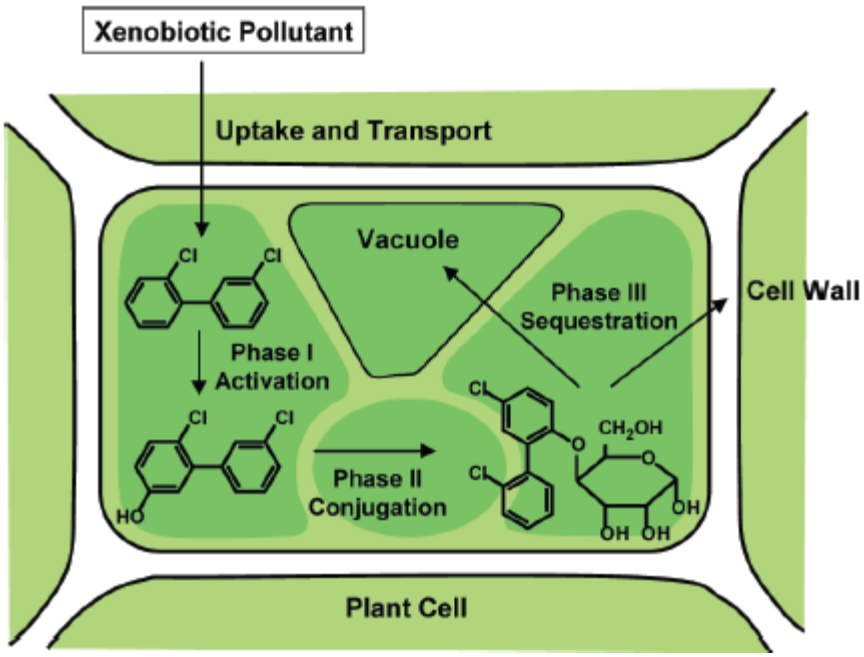


Figure 8. Three phases of the green liver model. Phase I, activation of the PCB by hydroxylation; Phase II, conjugation with a plant molecule (sugar); Phase III, sequestration of the conjugate into the vacuole or cell wall (Van Aken et al., 2010).

The initial steps in plant metabolism of PCBs involve oxidation of the biphenyl core, which is discouraged by the presence of electron-withdrawing chlorine atoms. Plant metabolism of PCBs appears therefore limited to tetrachlorinated and lower congeners. In some instances, lower chlorinated congeners are more recalcitrant than higher ones, suggesting the importance of substitution pattern (Van Aken et al., 2010). Zeeb et al., (2006) found pumpkin (*Cucurbita pepo* var. Howden) and zucchini (*Cucurbita pepo* var.

Senator) to have increased levels of congeners that contain four, five, or six chlorine atoms in the roots and shoots compared to the soil with higher chlorinated biphenyls, which may indicate that the plants are breaking down the highly chlorinated congeners and storing them in the lower chlorinated form. The rate in which PCBs metabolize within a plant is dependent on the plant species, the degree of chlorination and the substitution pattern (Van Aken et al., 2010).

Limits

Phytoremediation requires that contaminants be in the direct vicinity of the roots because the enzymes in the rhizosphere are active only in close proximity to the root (1 mm) for transformation of organic contaminants (Schnoor, 1997). Therefore, it is important to choose plants, alone or in combination, that are dense and able to extend deep in the soil. The amount of time required is also a major issue. Phytoremediation may require more time to achieve clean-up standards than other more costly alternatives such as excavation (Schnoor, 1997). Also, phytoremediation is limited by climate variation and seasonal effects. For example, perennial plants require at least a year to establish, and for organic compounds, at least three or more years are needed to allow for plant stabilization (Green and Hoffnagle, 2004). Fast growing plants that can establish a root system quickly are necessary in order to require less time. Phytoremediation may be used alone or with other technologies and when time is an important factor, excavation can be used with phytoremediation to restore the land and remediate areas excavation was not able to due to inaccessibility or cost reasons. In this case, phytoremediation will enhance MNR.

Many limitations are able to be resolved and prevented through proper planning. Conducting treatability studies early in the remedial investigations and feasibility studies (RI/FS) process reduces uncertainties associated with selecting the remedy, provides a sound basis for the record of decision (ROD), and minimizes the possibility of failure at full-scale implementation (U.S. EPA, 1993). Ways to ensure full growth of plants is by using fertilizers to replenish nitrogen, lime to restore pH, irrigation systems for dry areas, tilling tough soil before planting, the use of shade cloths for light sensitive plants, etc. depending on the site.

Additives

The use of additives to improve microbial communities, plant growth, contaminant transportation, and degradation has been used in several cases. Additives include randomly methylated-β-cyclodextrins (RAMED); fungi such as arbuscular mycorrhizal fungi (AMF); nitrogen fixing bacteria such as *Rhizobium meliloti* and *Sinorhizobium* meliloti; and citric acid amendments. RAMED is a non-toxic, biodegradable annular glucose-oligosaccharide commonly used in food and pharmaceutical industries, and has shown to significantly enhance aerobic PCBs biodegradation in bioreactors. RAMED is able to form PCB water-soluble inclusions that liberate PCB molecules from soil particles (Fava et al., 2002). Therefore, RAMED has the potential to enhance degradation of PCBs by increasing their bioavailability (Shen et al., 2009). AMF is able to enhance root physiology, enzyme activity, and root exudation. AMF along with *Rhizobium* and *Sinorhizobium* have shown to enhance PCB removal from soil and increase biomass of Alfalfa (Chen et al., 2005; Teng et al., 2010). Agents such as ethylenediamine tetra-acetic acid (EDTA) or organic acids, commonly found in

orange peels, will bind soil cations in both the inorganic soil matrix and organic matter itself, effectively disrupting the soil structure and promoting the release of humic substances, followed by increased availability of the weathered organic contaminants (Nardi et al., 2000; White et al., 2003; White et al., 2005). Additives in soil have the ability to increase degradation through chemical reactions and microbial enhancement, while reducing PCBs hydrophobic characteristics for easier extraction into plants.

Choosing a Plant

When determining what plant to use for an experiment, it is necessary that the plant is suitable for the climate and soil conditions and that it will be effective in removing PCBs (Figure 9; ITRC, 2001). The conditions of the land such as contaminant concentration, nutrient availability, and type of soil will be the first factors needed to determine if the use of plants will be a viable option. High levels of PCB contamination may cause the appearance of toxic symptoms in plants such as necrosis, curling of leaves, and stunted growth (Zeeb et al., 2006). The plants chosen for phytoremediation are typically known for their versatility and ability to grow in harsh, contaminated conditions. However, the plants ability to grow must be ensured before work can continue. Demnerova et al. (2002) found that birch grew in soil contaminated with 150 mg/kg of PCBs, different grasses and forbs were found in soil containing about 200 mg/kg of PCBs and goat willow was found in soil with 470 mg/kg. Zeeb et al. (2006) found *C. pepo* var. Goldrush, *C. pepo* var. Howden, *C. pepo* var. Senator and *F. arundinacea*, and *C. normalis* to grow in PCB contaminated soil (4200 ppm) without significantly decreasing its shoot heights compared to lower soil concentrations, however the biomass decreased for all of them except *F. arundinacea*. In addition to climatic and

soil conditions, the plant may need resistance to or tolerance of disease, heat, cold, insects, drought, chemicals, and stress (Pivetz, 2001). Treatability studies conducted during the RI/FS activities indicate whether the technology can meet the cleanup goals for the site. After the initial treatability study for the RI/FS, another one is conducted during the Remedial Design/ Remedial Action (RD/RA) activities and establishes the design and operating parameters for optimization of technology performance. (U.S. EPA, 1993)

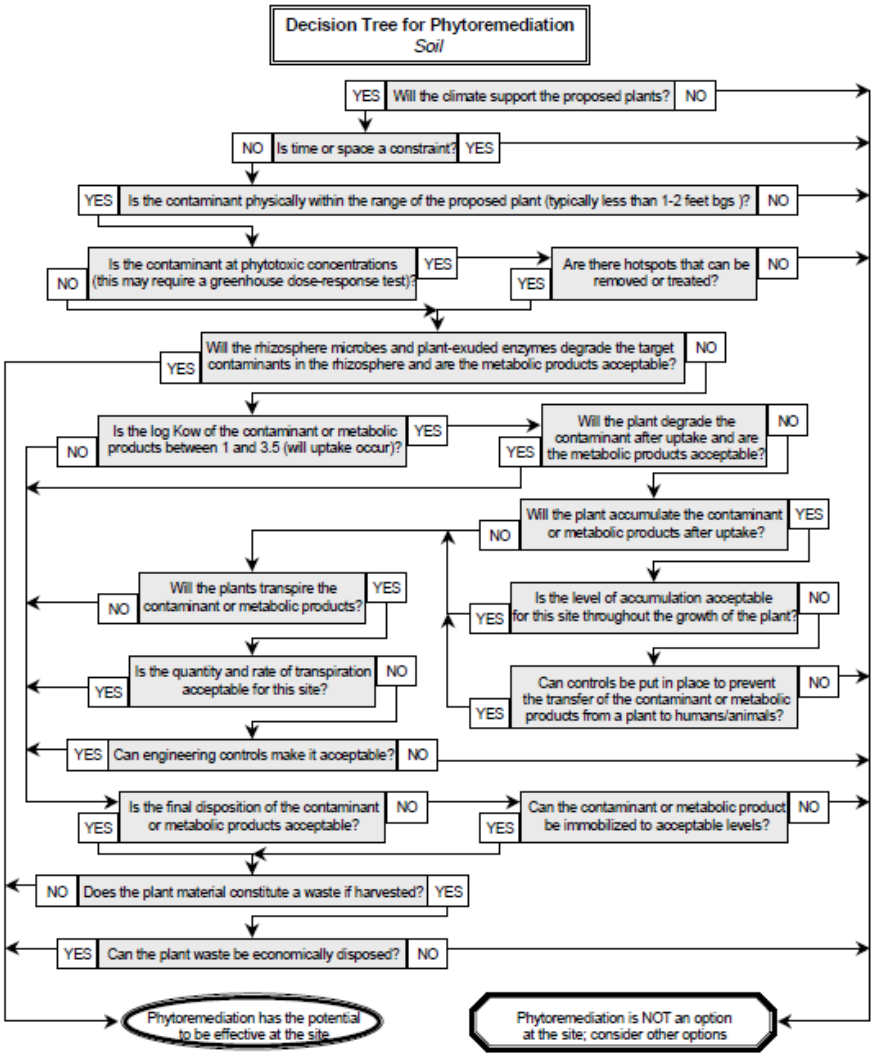


Figure 9. Decision Tree for Phytoremediation (ITRC, 2001).

Phytoextraction is more efficient when contaminants are stored in the shoot tissues because it will minimize harvesting and processing costs (Ficko et al., 2010). Plants that accumulate a majority of the PCBs in their roots would not be viable for this scenario. However, plants that accumulate PCBs primarily in their roots would be useful before excavation because the PCBs will be contained within the roots as well as the soil. If the plants are going to be left onsite for an area that does not plan on being developed in the near future, Brownfields, then a perennial plant known to influence the microbial community could be a better option. A plant that stores only a small amount of PCBs in their shoots, leaves, and stems are less likely to contaminate herbivores in the area.

Plant species that are long-term competitors and survivors under adverse changing conditions have an advantage (Pivetz, 2001). Native species to the area will be better to work with because it will not influence competitiveness amongst other plants and increase habitats. Native species are important for long-term plantings, however vigorous, locally adapted varieties of mostly nonnative forage grasses, legumes, or other species may be the most appropriate choices. These cultivated species can be considered initially with the eventual succession towards native species over time (ITRC, 2009).

Plants have diverse characteristics such as growth rates, versatility, population density, secondary metabolites, etc that can be utilized based on the needs of a specific site. Grasses provide a tremendous amount of fine roots in the surface soil which are effective at binding and transforming hydrophobic contaminants such as TPH, BTEX, and PAHs. Grasses are often planted between rows of trees to provide for soil stabilization and protection against wind-blown dust that can move contaminants off-site (Schnoor, 1997).

Legumes such as alfalfa, alsike clover, and peas can be used to restore nitrogen to poor soils. Tall fescue, rye, and reed canary grass have been used successfully at sites contaminated with petrochemical wastes. Alfalfa has been proposed as a suitable plant for rhizoremediation (Karlson et al., 1998) because of its biannual character, high yield, deep root system and high drought tolerance while having a high water consumption that could carry the pollutants to the rhizosphere (Villacieros et al., 2003). Hydrophobic contaminants do not translocate appreciably, so the top portion of grasses are not contaminated. Therefore, the system achieves phytoremediation within the rhizosphere and sorption to roots (Schnoor, 1997). The roots of many plant species are colonized by AMF, which subsequently facilitate host plant acquisition of soil phosphorous. AMF and symbiotic nitrogen-fixing bacteria are common beneficial microbes of monocotyledonous and leguminous plants allowing for increased microbial activity. Rhizobia colonize the roots of legumes where they fix atmospheric nitrogen, some of which can utilized for plant growth (Marx, 2004; Teng et al., 2010). Alfalfa also selectively stimulates the growth of PCB-degrading bacteria, such as *Pseudomonas fluorescens* F113 (Ryslava et al., 2003; Villacieros et al., 2003).

Tall fescue (*F. arundinacea)* and sedge (*C. normalis)* are perennial plants and have the ability to grow in highly contaminated soils (4200 ppm) without causing significant changes in their biomass (Zeeb et al., 2006). Tall fescue grows best in moist, clay environments high in organic matter, but also tolerates drought and is well adapted to a wide range of soils. Tall fescue is also well adapted to the "transition zone" of the United States where summers are too hot and humid for cool season grasses and winters too cold for warm season grasses. Tall fescue tolerates low fertility, but responds well to

fertilization at about 3 lbs. of actual nitrogen per 1,000 sq. ft. per year (Duble, 2011). Tall fescue is characterized by a relatively dense and extensive root system. Rooting depths of 2.5 feet are not uncommon when correct mowing, irrigation and fertilization practices are employed. The root system has the ability to penetrate, and survive in, compacted soils (Gibeault et al., 1972).

Common sedge (*Carex normalis*) is presently located on the eastern half of North America with Kansas being the most western state. Sedge has a rapid growth rate and a height of 5 feet at maturity. Sedge is low maintenance and provides a solid ground cover, preventing contaminated soils from blowing away and can achieve longer growing seasons than pumpkins in temperate climates (Whitfield Aslund et al., 2007). Sedge can grow up to 5 ft and fully matures after 20 years (USDA, 2011).

The Cucurbita family has been widely tested for its abilities to bioaccumulate contaminants and includes plants such as pumpkins *(Cucurbita pepo* cv Howden*)*, squash (*Cucurbita pepo* ssp. *Pepo* cv Goldrush and *Cucurbita pepo* ssp ovifera cv Zephyr), and zucchini (*Cucurbita pepo* ssp pepo cv Black Beauty and *Cucurbita pepo* cv Senator hybrid). Pumpkins have shown to accumulate a variety of persistent organic compounds such as DDE (White, 2000; White, 2001; White 2002; Mattina, 2000), DDT (Reimer, 2004), and chlordane (Mattina et al., 2004). *C. pepo* has a diffuse root system ranging from 40 to 187 cm, which is longer than other plants being tested, such as sedge (9-16 cm) and tall fescue (7-16 cm) (Whitfield et al., 2007). Zucchini has been tested for accumulating more contaminants than other plants, such as DDT (Reimer, 2004), PCDDs, PCDFs (Hülster et al., 1994), PCBs (White et al., 2005), p, p'-DDE (White et al., 2003), chlordane (Mattina et al., 2004), and heavy metals (Mattina et al., 2003).

Pumpkins are typically ready for harvest 95 to 120 days after planting and are able to spread out great lengths and climb. Setting up pumpkins so they are raised off the ground prevent cucumber beetles from eating holes into the leaves and flowers and possibly spreading diseases such as mosaic virus and bacterial wilt (Backyard Garden, 2011). Pumpkins' large aboveground biomass allows pumpkins to accumulate large absolute amounts of PCBs. Also, the leaves of cucurbits have large surface areas that result in high transpiration rates of water from the plant causing increased rates of water and nutrient transport in the xylem (Bell and Failey, 1991). The increased rate of translocation within the plant contributes to the increased movement from the soil to the shoots (Zeeb et al., 2006). Pumpkins have the ability to extract high levels of PCBs due to the root exudates that bind reversibly with POP molecules in soil to create a more hydrophilic complex. This allows the absorption into the roots and up the stems to be done more readily (Campanella and Paul, 2000). Also, *C. pepo* release high levels of low molecular weight antioxidants (LMWAO) causing a partial dissolution of the soil matrix and releasing bound pollutants (White et al., 2003; Luo et al., 2006; Whitefield Aslund et al, 2007). Cucurbits have root exudates that are different in composition than other plant exudates. Richardson and Backer (1982) found Cucurbits to have a high protein content and low total sugar content, with a high proportion of the sugar as monosaccharides.

Weeds are relatively new to phytoremediation and have several characteristics that allow them to be viable options. They are easy to cultivate and propagate, generally self-sustainable, relatively inexpensive, and are often hardier than many cultivated species (Ficko et al., 2010). Weeds are perennial species good at stabilizing, extracting, or degrading contaminants with their long life span. Weeds are proficient at growing in

inhospitable or disturbed locations, and may be able to tolerate and thrive in areas of high contamination (Ligenfelter and Hartwig, 2007; Ficko et al., 2010). Most perennial weeds possess special vegetative structures that allow them to reproduce asexually and survive. These perennial structures contain carbohydrates (food reserves, sugars) and numerous buds in which new plants can arise. Weeds have rhizomes which are belowground and thickened stems that grow horizontally in the upper soil layers. They can also have tubers which are enlarged rhizomes with compressed internodes. Other perennial weeds are able to store carbohydrates at the stem, known as bulbs, and modified roots that grow both horizontally and vertically, known as budding roots (Ligenfelter and Hartwig, 2007). Ficko et al. (2010) found the average shoot to root biomass ratio to be 5:1, which means there is a greater chance for weeds to translocate PCBs to their shoots.

Methods and Materials

The purpose of this paper is to run a quantitative meta-analysis by combining all available data and making direct comparisons using plants previously studied in order to answer the questions; 1) what plant is the most effective at remediating PCB contaminated soil, and 2) whether or not plants could be a viable option to be used solely to remediate PCB contaminated soil. Bringing the information together will determine if plants are presently a viable option for the remediation of PCB contaminated soils or if there is still more testing necessary before its removal efficiencies are comparable to current strategies.

The meta-analysis was conducted by identifying investigations of phytoremediation of PCB contaminated soil using field and lab work. In order to do so, a search criterion was established to find research articles pertaining to PCB phytoremediation. Criteria included papers measuring soil changes, concentration levels in the plant, or mass uptake of PCBs. Any articles with at least one of these criteria were used for the analysis. After establishing the criteria, a search was conducted for the results of investigations published in the peer- reviewed literature, using the VCU library resources. Only peer-reviewed articles in which an original copy was attainable were used. For example, data summarized in a table by a third party were not used unless the original research was retained. Articles summarizing other people's work were not used if the original, published work was unobtainable.

Plant species and plant types were the independent variables for the comparisons. The categories for plant groups were legumes, grasses, crops, weeds, and cucurbits and were determined based on how the original researchers categorized the plants. The data

were organized into several categories for comparisons and were the dependent variables. The main categories organized for comparison include root concentration, shoot concentration, change in PCB soil concentration, PCB mass uptake into root, PCB mass uptake into shoot, and PCB mass uptake in the entire plant. The extra variables that would need to be accounted, confounding variables, include the amount of time the plants were grown, Aroclor number, initial PCB soil concentration, additive use and whether the experiment was conducted in a greenhouse or in the field. In order to directly compare concentrations, all root, shoot, and soil concentrations were converted to parts per million (ppm). Mass uptake was converted to micrograms (μg). To account for the length of time the plants were grown, mass uptake and soil PCB concentration change were converted to rates on a per month basis. A list of the plants used can be found in the beginning of the paper and the raw data can be found in Appendix A.

Statistical software JMP 8.0.2 was used to run an analysis of covariance (ANCOVA) with a Tukey's post-hoc test in order to compare the different species of plants to determine which demonstrated the greatest soil changes, concentrations in the roots or shoots, and total accumulation in plants. The ANCOVA accounted for Aroclor number, pot vs field study, initial PCB soil concentration, and the use of additives. Variables were removed if a majority of the values were missing, not different, or directly related to another variable. For instance, the field tests consisted of the lowest initial PCB soil concentration, then location of testing would be removed because it would cause the statistics to over account for the differences. Also, additives have shown improvement throughout various tests (White et al., 2005; Chen et al., 2005; Chen et al., 2009; Xu et

al., 2010; Ten et al., 2010) so when additives appeared to be a negative influence, the variable was not accounted for.

Root and Shoot PCB Concentrations

Root and shoot concentrations were compared independently of each other. Table 7 shows the number of samples used for the plant groups. The data were transformed using natural log to make the data normally distributed. Plant species and groups were compared to determine what plant or group had the greatest ability to concentrate PCBs. Plant species were then compared based on their plant group to account for differences among biomass. The cucurbit and weed group have the most samples available for comparison, however the weed group has only one sample per plant and comes from one investigation (Fick et al., 2010). Plants in the weeds group will not be included when comparing the individual root and shoot concentrations because of the sample number of one. Factors that were accounted for include Aroclor number, initial PCB soil concentration, use of additives, and whether testing took place in a field. Bioaccumulation factors (BAF) were also compared among the plant species and group. The cube root transformation was taken for the BAF data to generate normal distribution.

Table 7. Number of root and shoot concentration samples.

Plant Group	Root	Shoot	References
Cucurbit	24	22	White et al., 2005; Zeeb et al., 2006; Whitfield Aslund et al., 2007; Whitfield Aslund et al., 2008; Low et al., 2010
Grass	6	6	Zeeb et al., 2006; Whitfield Aslund et al., 2007
Legume	10	10	White et al., 2005; Zeeb et al., 2006; Teng et al., 2010; Xu et al., 2010
Weed	36	51	Ficko et al., 2010

Total PCB Uptake

The rate of PCB uptake per month (μg/mo) in the shoots and total plant were compared between plant species and group (Table 8). The total plant uptake includes the amount accumulated in the roots and shoots. It does not include the amount in the fruits of the plants. In order for the data to be normally distributed, the data were transformed using natural log. There were only four articles with Zeeb et al. (2006) accounting for most of the data. The lack of recording plant biomass by researchers prevented further data for this comparison. The direct comparisons between the plants tested by Zeeb et al., (2006) allowed for better interpretation of root and shoot concentrations.

Table 8. Number of plant species used to compare shoot and plant total PCB accumulation (μg) per month. Two numbers indicate a different number of samples for shoot and total plant (shoot samples/plant samples). A single number indicates same for both.

Plant	Type	Shoot and Plant Uptake	References
Pumpkin (*Cucurbita pepo cv Howden*)	Cucurbit	2/6	Zeeb et al., 2006 Low et al., 2011
Squash (*Cucurbita pepo cv Goldrush*)	Cucurbit	1	Zeeb et al., 2006
Zucchini (*Cucurbita pepo cv Senator hybrid*)	Cucurbit	2	Zeeb et al., 2006
Reed canary grass (*Phalaris arundinacea*)	Grass	1	Zeeb et al., 2006
Rye grass (*Lolium multiflorum*)	Grass	1	Zeeb et al., 2006
Tall fescue (*Festuca arundinacea*)	Grass	3	Zeeb et al., 2006
Sedge (*Carex normalis*)	Weed	2	Zeeb et al., 2006
Alfalfa (*Medicago sativa*.)	Legume	7	Zeeb et al., 2006; Teng et al., 2010; Xu et al., 2010
Soybean (*Glycine max*)	Legume	2	Zeeb et al., 2006

PCB Concentration (ppm) Change in Soil

The PCB concentration changes in soil were compared on a per month basis (change in concentration/mo). To account for differences in unplanted control soils, the change in PCB concentration for planted soil was subtracted by the decrease found in the unplanted controls. If soil depletions were less in the planted sample than the control, that

sample was removed. The number of plants used for testing soil changes can be found in Table 9. Due to the large range of initial PCB soil concentrations (0.45-4200 ppm), the data were split in two groups to help lower the influence of soil change among comparisons. Low soil concentrations included initial PCB soil concentrations less than 50 ppm and high soil concentrations included initial PCB soil concentrations equal to or greater than 50 ppm. 50 ppm was chosen because soil with concentrations greater than or equal to 50 ppm must be treated as hazardous waste according to TSCA. The data for both groups were normally distributed.

Table 9. Number of plant species and group samples used to compare PCB concentration changes in the soil.

Plant	Plant Type	All Soil	Soil High	Soil Low	All Soil References
Horseradish (*Armoracia rusticana*)	Crop	2	2	0	Martina et al., 2009
Rice (*Oryza sativa*)	Crop	2	0	2	Chen et al., 2009
Tobacco (*Nicotiana tabacum*)	Crop	6	6	0	Gichner et al., 2007; Martina et al., 2009
Deertongue (*Panicum clandestinum*)	Grass	2	2	0	Dzantor et al., 2000; Chekol et al., 2003
Reed canarygrass (*Phalaris arundinacea*)	Grass	6	6	0	Dzantor et al., 2000; Dzantor and Woolston, 2001; Chekol et al., 2003
Ryegrass (*Lolium perenne L*)	Grass	2	0	2	Chen et al., 2009
Switchgrass (*Panicum virgatum*)	Grass	2	2	0	Dzantor et al., 2000; Chekol et al., 2003
Tall fescue (*Festuca arundinacea*)	Grass	4	2	2	Dzantor et al., 2000; Chekol et al., 2003; Chen et al., 2009
Alfalfa (*Medicago sativa*.)	Legume	15	3	12	Chekol et al., 2003; Chen et al., 2005; Martina et al., 2009; Teng et al., 2010; Xu et al., 2010
Flatpea (*Lathyrus sylvestris*)	Legume	1	1	0	Dzantor and Woolston, 2001
Flatpea (*Lathyrus sylvestris*)	Legume	4	4	0	Dzantor et al., 2000; Dzantor and Woolston, 2001; Chekol et al., 2003
Sericea lespedeza (*Lespedeza cuneata*)	Legume	2	2	0	Dzantor et al., 2000; Chekol et al., 2003
Black nightshade (*Solanum nigrum*)	Weed	3	3	0	Martina et al., 2009

Results

Root Concentrations

Cucurbits seemed to consistently have the highest root concentration compared to grasses, legumes, and weeds (Table 10). All of the cucurbits, tall fescue, sedge, and soybean had the highest median root concentrations. Alfalfa was the least successful at concentrating PCBs within its roots. Regardless of the differences seen in Table 10, there was no significant difference in root concentrations between any of the plant species ($F_{39;39}$=1.62, p=0.12). The ANCOVA accounted for initial PCB soil concentration, use of additives, Aroclor number, and whether the experiment was conducted in the field or not. Initial PCB soil concentration and additives had a significant influence on the root concentration for each of the plant species.

After accounting for the same variables, there was a significant difference for plant type ($F_{3;3}$=3.16, p=0.031), however based on the post hoc Tukey comparison, the groups are not significantly different. Initial soil, additives, and Aroclor number had a significant influence over PCB concentration found in the roots ($p<0.05$) among the groups. Within the plant groups, no significant difference in root concentration was found between plant species ($p>0.05$).

Seventeen of the twenty-four cucurbits tested had root BAFs greater than one (ranged from 1.9 to 4.2). Tall fescue and sedge's highest BAF was around 1.5, which is not as effective as most of the cucurbits. Black mustard and white heath aster had the highest BAF's with 10 and 6.45, but there was only one sample for both of them. Therefore it is unclear if these are typical concentrations. BAF's were calculated and a significant difference was found among plant species ($F_{39;39}$=2.03, p=0.04), but not plant

group ($F_{3;3}$=1.81, p=0.16). Black mustard was found to have significantly higher BAF than purple loosestrife.

Table 10. Descriptive statistics for PCB concentrations in roots based on plant group and species. No significant differences were found among plant species within the plant group groups after accounting for initial PCB soil concentration, use of additives, Aroclor number, and whether the experiment was done in the field. The top six weed plants with the highest root concentration are shown.

Plant	**n**	**Root Conc Median [BAF]**	**Root Conc Range [BAF]**	**References**
Cucurbit	24	282.5 [2.74]	21.5-3200 [0.38-4.19]	
Zucchini (*C. pepo cv Senator hybrid*)	2	945 [1.8]	290-1600 [0.38-3.22]	Zeeb et al., 2006
Zucchini (*C. pepo cv Black Beauty*)	5	400 [3.8]	85-440 [0.81-4.19]	White et al., 2005
Squash (*C. pepo cv Goldrush*)	2	332.5 [1.54]	75-590 [0.71-2.36]	White et al., 2005; Whitfield Aslund et al., 2007
Summer Squash (*C. pepo ovifera cv Zephyr*)	4	332.5 [3.16]	50-410 [0.48-3.9]	White et al., 2005
Cucumber (*Cucumis sativus cv Marketmore*)	4	270 [2.57]	100-375 [0.95-3.57]	White et al., 2005
Pumpkin (*C. pepo cv Howden*)	7	60 [2.86]	21.5-3200 [0.76-3.71]	Zeeb et al., 2006; Whitfield Aslund et al., 2007; Whitfield Aslund et al., 2008; Low et al., 2010
Grass	7	60 [0.66]	15-6500 [0.33-1.55]	
Tall fescue (*Festuca arundinacea*)	4	154.5 [0.83]	15-6500 [0.33-1.55]	Zeeb et al., 2006; Whitfield Aslund et al., 2007
Rye grass (*Lolium multiflorum*)	1	60 [0.67]		Zeeb et al., 2006
Reed canary grass (*Phalaris arundinacea*)	1	46 [0.51]		Zeeb et al., 2006
Barnyard grass (*Echinochloa crusgalli)*	1	24 [0.77]		Ficko et al., 2010
Weed	35	24 [1.53]	2.5-2200 [0.15-10]	
Sedge (*Carex normalis*)	3	66 [0.52]	34-2200 [0.38-1.47]	Zeeb et al., 2006; Whitfield Aslund et al., 2007
White heath aster (*Symphyotrichum ericoides*)	1	200 [6.45]		Ficko et al., 2010
Tufted vetch (*Vicia cracca*)	1	110 [3.55]		Ficko et al., 2010
Canada Goldenrod (*Solidago canadensis*)	1	77 [2.48]		Ficko et al., 2010
Canada thistle (*Cirsium arvense*)	1	50 [1.61]		Ficko et al., 2010
Yellow foxtail (*Setaria pumila*)	1	48 [1.55]		Ficko et al., 2010

Table 10 Continued

Plant	n	Root Conc Median [BAF]	Root Conc Range [BAF]	References
Legume	10	0.3253 [0.48]	0.115-2000 [0.18-1.11]	
Soybean (*Glycine max*)	2	1050 [0.79]	100-2000 [0.48-1.11]	Zeeb et al., 2006
White lupin (*Lupinus albus*)	1	19 [0.18]		White et al., 2005
Alfalfa (*Medicago sativa*.)	7	0.2678 [0.49]	0.115-53 [0.26-0.59]	Zeeb et al., 2006; Teng et al., 2010; Xu et al., 2010

Shoot Concentrations

Shoot PCB concentrations range greatly for the plants. The highest shoot concentration was from sedge (*Carex normalis*) at 470 ppm followed by tall fescue (*Festuca arundinacea*), 98 ppm, and pumpkin (*C. pepo* cv Howden), 84 ppm. Tufted vetch and ladysthumb were the only plants to have a shoot BAF greater than one. Cucurbits and weeds had higher shoot concentrations (Table 11) ($F_{3;3}$=6.41, p=0.001) than legumes while accounting for initial PCB soil concentration, Aroclor number, additive use, and whether the experiment was performed in the field. Initial soil PCB concentration and Aroclor number had a significant influence ($p<0.05$) on PCB uptake into shoots.

There was not a significant difference among plant species in any of the groups ($p>0.05$), but when comparing plant species individually, there was a significant difference ($F_{39;39}$=2.37, p=0.017) in shoot concentrations. Sedge (*Carex normalis*) and pumpkin (*C. pepo cv Howden*) had a shoot concentration significantly higher than soybean (*Glycine max*). None of the confounding variables had a significant influence on the data ($p>0.05$). BAF's were calculated and there were no differences among plant species ($F_{39;39}$=1.22, p=0.31), or plant groups ($F_{3;3}$=2.66, p=0.057).

Table 11. Descriptive statistics for PCB concentration in the shoots based on plant group and plant species. Differences in capitalized letters represent differences between plant groups and comparisons within a group (Grasses). Under-cased letters represent significant differences between individual plants (excluding the weeds group) ($p<0.05$). Due to space limitations, the top seven median weed shoots plant species are displayed.

Plant	n	Shoot conc median (ppm) [BAF]	Shoot conc range (ppm) [BAF]	References
Cucurbits[A]	22	13.5 [0.13]	3.5-84 [0.007-0.538]	
Zucchini (*C. pepo cv Black Beauty*)[ab]	5	22 [0.21]	15-50 [0.143-0.476]	White et al., 2005
Zucchini (*C. pepo cv Senator hybrid*)[ab]	2	20.5 [0.065]	11-30 [0.007-0.122]	Zeeb et al., 2006
Summer Squash (*C. pepo ovifera cv Zephyr*)[ab]	4	17.5 [0.167]	5-25 [0.048-0.238]	White et al., 2005
Squash (*C. pepo cv Goldrush*) [ab]	2	11.5 [0.074]	10-13 [0.052-0.095]	White et al., 2005, Zeeb et al., 2006
Pumpkin (*C. pepo cv Howden*)[a]	5	11 [0.149]	3.5-84 [0.02-0.538]	Whitfield Aslund et al., 2008; Low et al., 2010
Cucumber (*Cucumis sativus cv Marketmore*)[ab]	4	10 [0.095]	5-35 [0.048-0.333]	White et al., 2005
Weed[A]	35	2.75 [0.24]	0.37-470 [0.07-1.13]	
Sedge (*Carex normalis*) [a]	3	19 [0.211]	13-470 [0.111-0.029]	Whitfield Aslund et al., 2007, Zeeb et al., 2006
Wild carrot (*Daucus carota*) [ab]	2	12.3 [0.73]	3.7-21 [0.67-.79]	Ficko et al., 2010
Heath aster (*Symphyotrichum ericoides*) [ab]	1	17 [0.55]		Ficko et al., 2010
Black Mustard (*Brassica nigra*) [ab]	1	13 [0.42]		Ficko et al., 2010
Goldenrod (*Solidago canadensis*) [ab]	1	8.3 [0.27]		Ficko et al., 2010
Sow thistle (*Sonchus asper*) [ab]	2	3.6 [0.19]	1.35-5.86 [0.11-0.29]	Ficko et al., 2010
Redroot pigweed (*Amaranthus retroflexus*)[ab]	1	5.7 [0.18]		Ficko et al., 2010

Plant	n	Shoot conc median (ppm) [BAF]	Shoot conc range (ppm) [BAF]	References
Grass[AB]	7	3.2 [0.021]	1.1-98 [0.012-0.10]	
Tall fescue (*Festuca arundinacea*)[ab]	4	6.65 [0.029]	1.7-98 [0.019-0.104]	Whitfield Aslund et al., 2007, Zeeb et al., 2006
Barnyard Grass (*Echinochloa crusgalli*)[ab]	1	2.5 [0.08]		Ficko et al., 2010
Rye grass (*Lolium multiflorum*)[ab]	1	1.3 [0.014]		Zeeb et al., 2006
Reed canary grass (*Phalaris arundinacea*)[ab]	1	1.1 [0.012]		Zeeb et al., 2006
Legume[B]	10	0.05 [0.055]	0.003-8 [0.001-0.09]	
White lupin (*Lupinus albus*)[ab]	1	8 [0.076]		White et al., 2005
Soybean (*Glycine max*)[c]	2	1.86 [0.002]	0.32-3.4 [0.001-0.004]	Zeeb et al., 2006
Alfalfa (*Medicago sativa*.)[ab]	7	0.04 [0.059]	0.003-1.2 [0.007-0.09]	Zeeb et al., 2006, Teng et al., 2010, Xu et al., 2010

Shoot and Plant Uptake

Zeeb et al. (2006) measured the total PCB uptake into shoots and roots for a variety of cucurbits, grasses, and legumes. After two months of growing on three soils with different concentrations, tall fescue accumulated greatest amount of PCBs in its roots (5700 μg) at the highest PCB concentrated soil (4200 ppm), which was over 20-fold greater than pumpkin (260 μg), however pumpkin accumulated more PCBs in its shoots (290 μg) and had a better translocation factor of 1.1 (Zeeb et al., 2006). At 90 ppm soil PCB concentration, sedge had the highest translocation factor (2.94) recorded to date, but only extracted 60 μg in its shoots. Zucchini (*C. pepo* cv Senator) accumulated the most PCBs in the entire plant when grown in soil at 90 ppm. Zucchini (Senator) accumulated more PCBs at 90 ppm, than greater contaminated soil (4200 ppm). The high

concentration PCBs inhibited plant growth to only a quarter of the biomass found in the lesser contaminated soil of the same experiment.

Overall, the plant with the highest rate of shoot and plant uptake was pumpkin followed by tall fescue (Table 12). PCBs were mainly found in the roots of the plants. Plants were compared while taking into account additive use and initial PCB soil concentration since there were no differences among Aroclor number. Also, field experiments coincided with the lowest initial PCB concentrations in the soil causing initial PCB soil concentrations to have a greater influence. Cucurbits significantly accumulated more PCBs in its shoots than legumes ($F_{3;3}$=6.35, p=0.005), however, there was no difference between the amount of PCBs in shoots among all of the species ($F_{8;8}$=2.04, p=0.136). However, pumpkin (*C. pepo* cv Howden) and tall fescue (*Festuca arundinacea*) significantly accumulated more PCBs in the entire plant than alfalfa (*Medicago sativa*) ($F_{8;8}$=4.68, p=0.005) among plant species, but was not significantly different than the other plants. Cucurbits also had a significantly higher plant uptake rate than the legume group ($F_{3;3}$=5.97, p=0.004).

Table 12. Shows the descriptive statistics for shoot and total plant uptake of PCBs per month planted (μg/mo). No significant difference was found between the plants for shoot uptake, but a different letter represents a significant change for the total plant uptake. For "n", the first number corresponds to the number of shoot samples and the second refers to the number of total plant uptake samples. A single number represents the same number for both.

Plant	n	Shoot Uptake per mo Median	Shoot Uptake per mo Range	Plant Uptake per mo Median	Plant Uptake per mo Range	References
Pumpkin (*C. pepo* cv Howden)[a]	2/6	88	30-145	1536	147-2925	Zeeb et al., 2006, Low et al., 2011
Tall fescue (*Festuca arundinacea*)[a]	3	30	2.85-75	175	128-275	Zeeb et al., 2006
Sedge (*Carex normalis*)[ab]	2	30	30-30.5	20	19-22	Zeeb et al., 2006
Zucchini (*C. pepo* cv Senator hybrid)[ab]	2	28.5	24.5-32.5	107	76-138	Zeeb et al., 2006
Squash (*C. pepo* cv Goldrush)[ab]	1	27.5		100		Zeeb et al., 2006
Soybean (*Glycine max*)[ab]	2	3.425	0.85-6	30	18-41	Zeeb et al., 2006
Rye grass (*Lolium multiflorum*)[ab]	1	1.65		401		Zeeb et al., 2006
Alfalfa (*Medicago sativa*.)[b]	7	2.2	0.055-2.2	7	0.04-18	Teng et al., 2010; Xu et al., 2010

Whitfield Aslund et al. (2007) tested uptake based on an area basis (m^2) for plants growing in soil contaminated with a mean of 46 ppm (range 0.6-200 ppm) for eight weeks. Tall fescue accumulated more PCB overall per m^2 (2,300 $\mu g/m^2$) than pumpkin (*Cucurbita pepo* cv Howden) (1,600 $\mu g/m^2$), but pumpkin extracted more PCBs in the shoots (1,500 $\mu g/m^2$) than tall fescue (800 $\mu g/m^2$). In the same experiment (Whitfield Aslund et al., 2007) sedge was found to accumulate more PCBs in both its roots (4,800 $\mu g/m^2$) and shoots (2,000 $\mu g/m^2$) than pumpkin and tall fescue. Ficko et al., (2010) tested PCB accumulation using weeds and pumpkin (*C. pepo cv Howden*) determined PCB removal per m^2 at different nominal densities that allow for optimal growth for two different sites where soil concentrations were 31 ppm and 4.7 ppm. The use of a density value increased the total potential shoot extraction of ten species from the higher contaminated site to be greater than pumpkin, 1,500 $\mu g/m^2$, and in the two best, red clover (*Trifolium pratense*), the shoot extracted 110,000 $\mu g/m^2$, and lady's thumb (*Polygonum persicaria*), the shoot extracted 42,000 μg/m2. Nine species from the lower contaminated site extracted more PCBs than pumpkin, 2,100 $\mu g/m^2$, and in two cases, Ragweed (*Ambrosia artemisiifolia*) and New England aster (*Symphyotrichum novae-angliae*), shoot extracted 14,000 $\mu g/m^2$.

Zeeb et al. (2006) conducted their experiments in trays (18cm x 27cm x 6cm). Therefore to get the total amount extracted per meter, the area needs to be converted (0.18 m x .27cm) to meters. Pumpkin and tall fescue accumulated 11,300 $\mu g/m^2$ and 121,400 $\mu g/m^2$ mg in the entire plant when planted at 4200 ppm. When planted at 250 ppm, pumpkin (7,200 $\mu g/m^2$) accumulated more than tall fescue (6,000 $\mu g/m^2$) and

squash (5,300 μg/m^2). At 90 ppm, zucchini (senator) extracted 5,800 μg/m^2 throughout the plant.

PCB Concentration (ppm) Change in Soil

At low PCB concentrations in the soil (<50 ppm), tall fescue showed the greatest change in soil per month (0.33 ppm/mo) (Table 13). There was little difference between the plant groups ($F_{2;2}$=0.19, P=0.83) or plant species ($F_{3;3}$=0.54, P=0.66) at the low PCB soil concentrations. There was a significant influence by the initial PCB concentration in the soil and the use of additives when comparing plant species and plant group for the low soil concentration group ($p<0.05$).

At high PCB soil concentrations (≥50 ppm), tobacco showed the greatest depletion rate per month (14.6 ppm/mo) (Table 14). For the higher concentrated soil, no difference was found between plant groups ($F_{4;4}$=1.48, p=0.25) or plant species ($F_{10;10}$=0.60, p=0.80). Initial PCB soil concentration and Aroclor number were not significant influences when comparing the soil concentration changes among plant groups ($p>0.05$).

Table 13. Descriptive statistics for plant species and plant groups' ability to decrease PCB soil concentration per month in initial PCB soil concentrations less than 50 ppm. There were no significant differences in soil PCB change rate among the plant species or plant group.

Plant low	**n**	**Mean per mo**	**Std Error**	**References**
Tall fescue (*Festuca arundinacea*)	2	0.33	0.059	Chen et al., 2009
Rice (*Oryza sativa*)	2	0.264	0.059	Chen et al., 2009
Ryegrass (*Lolium perenne L*)	2	0.256	0.059	Chen et al., 2009
Alfalfa (*Medicago sativa*.)	12	0.142	0.027	Chen et al., 2005; Chen et al., 2009; Teng et al., 2010; Xu et al., 2010
Plant Group	**n**	**Mean per mo**	**Std Error**	
Grass	4	0.295	0.048	
Crop	2	0.264	0.059	
Legume	12	0.142	0.027	

Table 14. Descriptive statistics for plant species and plant groups' ability to decrease PCB soil concentration in one month in soil contaminated with greater than 50 ppm. No significant differences were found among plant species or plant group.

Plant	**n**	**Mean per mo**	**Std Error**	**References**
Tobacco (*Nicotiana tabacum*)	3	14.8	6.36	Martina et al., 2009
Alfalfa (*Medicago sativa*.)	3	9.7	5.67	Chekol et al., 2003; Martina et al., 2009
Switchgrass (*Panicum virgatum*)	2	9.0	6.88	Dzantor et al., 2000; Chekol et al., 2003
Black nightshade (*Solanum nigrum*)	3	8.7	5.38	Martina et al., 2009
Sericea lespedeza (*Lespedeza cuneata*)	2	7.9	6.88	Dzantor et al., 2000; Chekol et al., 2003
Deertongue (*Panicum clandestinum*)	2	7.6	6.88	Dzantor et al., 2000; Chekol et al., 2003
Tall fescue (*Festuca arundinacea*)	2	7.1	6.88	Dzantor et al., 2000; Chekol et al., 2003
Plant	**n**	**Mean per mo**	**Std Error**	**References**
Flatpea (*Lathyrus sylvestris*)	4	6.5	6.07	Dzantor et al., 2000; Dzantor and Woolston, 2001; Chekol et al., 2003
Horseradish (*Armoracia rusticana*)	2	4.8	6.46	Martina et al., 2009
Reed canarygrass (*Phalaris arundinacea*)	6	4.0	5.52	Dzantor et al., 2000; Dzantor and Woolston, 2001; Chekol et al., 2003
Burr medic (*Medicago polymorpha*)	1	2.1		Dzantor and Woolston, 2001
Plant group	**n**	**Mean per mo**	**Std Error**	
Crop	5	10.8	3.57	
Weed	3	8.73	3.87	
Legume	10	7.4	3.18	
Grass	12	6	3.61	

Discussion

Analysis of Covariates

All of the comparisons were most affected by the initial PCB soil concentration. This result makes sense because the more PCBs available in the soil and in close proximity to the roots allow for greater uptake and degradation opportunities. This outcome is evident when comparing PCB root concentrations in pumpkin (*C. pepo* cv Howden) growing in soil contaminated at 22 ppm and 2.7 ppm and there is a difference of 40 ppm between the two root concentrations (Whitland Aslund et al., 2008). Also, tall fescue (*C. normalis*) grown in three soil concentrations of 90 ppm, 250 ppm, and 4,200 ppm, had root concentrations of 59 ppm, 250 ppm, and 6,500 ppm respectively (Zeeb et al., 2006). Weeds however accumulated more PCBs in lower contaminated soil without losing much biomass. When concentrations in the soil are too high, plants do not grow as much and therefore accumulate less than they would in lower contaminated soil. When soil concentrations are too high for plants to grow, phytoremediation would not be the first, sole option.

The use of additives appeared to consistently improve plant growth, contaminant transportation, and degradation. Additives include randomly methylated-β-cyclodextrins (RAMED); fungi such as arbuscular mycorrhizal fungi (AMF); nitrogen fixing bacteria such as *Rhizobium meliloti* and *Sinorhizobium* meliloti; and citric acid amendments. Additives always had a positive influence on the amount of PCB accumulation into the plant. Additives have the ability to increase microbial numbers, assist in PCB breakdown, make PCBs more mobile, and assist the plant in growing. RAMED and citric amendments appeared to work best because they were capable of breaking down PCBs

alone. They performed better with plants and should continue to be tested and used in the field.

Aroclor number also influences the PCB uptake and accumulation found in the shoots as indicated by lower Aroclor numbers having greater uptake than higher Aroclor numbers. The characteristics of highly chlorinated biphenyls cause the PCBs to bind more tightly to the soil and not translocate into the shoots as well as lower chlorinated biphenyls. Higher chlorinated congeners require more time for dechlorination to take place to allow easier transport into the roots and degradation. However this was not seen in the study. Comparisons of root concentrations, shoot concentrations, changes in soil concentration for high levels of contamination displayed contradicting results. In each scenario, Aroclor number was found to be significant, but lower Aroclor numbers had the lowest concentration levels and soil reduction rates. It appears that other factors in the experiment had a stronger influence on the outcome.

Planting in the field allowed for greater plant biomass than when the plants were grown in a pot under greenhouse conditions. The ability to grow better in the field is likely due to the ability of the roots to spread out. However, better accumulation was found in potted plants. The inability of roots to stretch out and grow allowed for denser root formations in the soil and a lesser biomass could have influenced the PCB concentration. Overall, the initial PCB concentration in the soil has the greatest effect over plant concentration, plant uptake, and soil depletion.

It is unclear at this point the role plant density has on total accumulation. A densely planted area would likely decrease plant concentrations, but increase the total amount of PCB uptake. Increasing the density of the plants would increase root to soil

contact and the increased nutrient competition between plants under crowded conditions could induce increased production of root exudates associated with the mobilization of PCBs from soil into plant roots (Wang et al., 2004; Kelsey et al., 2006; Whitfield Aslund et al., 2008). Cucurbits planted too dense not only have less biomass per plant, but also have less biomass/m^2 (White et al., 2006; Whitfield Aslund et al., 2008) even with the use of fertilizer so it is important to know ideal planting densities.

Root and Shoot Concentration

The ability to accumulate PCBs in plant roots is the first step in phytoextraction. Plants typically take in PCBs that are in the direct proximity of the roots and therefore a dense, branching root system would be beneficial for PCB uptake from soil. Initial concentration of PCBs in soil has a great influence on the final concentration found in the roots due to PCB availability. When comparing plant type, cucurbits and grasses had the highest root concentration (Table 10). Cucurbits have long diffuse root systems and typically have a higher biomass than the other plant types. Therefore, it would appear based on concentrations that cucurbits accumulate more total PCBs in their roots. Pumpkin accumulated the highest concentration of PCBs in its roots compared to the other cucurbits, but not statistically significant. The cucurbit family shares similar qualities when it comes to exudates and secondary plant metabolite in the rhizosphere. The consistent concentration levels for the cucurbit family are encouraging because it allows for their PCB accumulation rates to be better understood. Tall fescue (*Festuca arundinacea*) accumulated the highest concentration of PCBs in its roots, but it is unclear whether or not it accumulated more PCBs than plants in the cucurbit group due to having a lower total biomass. Among the grass species, tall fescue accumulated much more than

sedge and when grown at the same soil concentration, had double the root concentration on two occasions (Zeeb et al., 2006). However, sedge accumulated more than tall fescue when grown in the field (Whitfield Aslund et al., 2007) but not by a large amount like the pot experiments.

Soybean had the greatest root concentration among the legume plants, but compared to other plants at the same soil concentration levels, it was not as effective. Alfalfa consistently had the lowest PCB concentrations in its roots. One main reason is that a majority of its samples came from research that used low initial PCB soil concentrations. However, even when Alfalfa was tested at higher PCB soil concentrations, the root concentration continued to be less than other plant species. Alfalfa's low root concentrations were not expected due to legumes' ability to create a tripartite symbiosis with AMF and *Rhizobium* bacteria in the rhizosphere and its extensive, deep root system. Some weeds had high root concentrations, but they were still not as good as the cucurbits, sedge, or tall fescue, and without more samples it is difficult to know if they will always perform as well.

The bioaccumulation factor (BAF) determines whether plants are able to accumulate and concentrate PCBs at higher levels than the surrounding soils. The ability to accumulate PCBs at higher concentrations than the surrounding soil is important because it means that PCBs are being drawn to the roots when they take in water and other nutrients from the soil. Plants grown in the same soil and conditions but unable to accumulate as much PCBs indicates that the root system's ability to spread out and release a large amount of metabolites in the soil is more effective than other root systems.

Plants in the Cucurbit group consistently had higher BAF's, which is expected due to their extensive root systems and ability to release large amounts of metabolites.

Plants with higher root concentrations typically have a higher shoot concentration compared to other plants (Tables 10 and 11). Shoot concentrations are much less than root concentrations due to the characteristics of PCBs, which makes phytoremediation harder to successfully accomplish. Instead, remedies that take advantage of higher root concentrations will be needed for these high concentrations of PCBs in the roots. Concentrations of PCBs in shoots do not indicate what plant species removed the most PCBs out of the soil because plants have different biomasses. Direct comparisons concentrations are not sufficient to compare different plants' abilities to remove PCBs from soil until the biomasses are included. Including biomasses will determine the amount of PCBs extracted into the plant and how much was therefore removed in a given area.

Uptake of PCBs

Total mass uptake of PCBs is important because concentration does not clarify biomass differences, and how the species growth was affected by the soil concentration. It is not possible to determine the amount of degraded PCBs, so analysis must be done as though no breakdown occurred. Measurements of total PCB uptake into plants came from four studies and two of them only tested alfalfa at low soil concentrations. Therefore it is difficult to judge on the overall consistency. It does show accumulation differences caused by the initial concentration in soil and allows for direct comparisons without as many confounding variables. Plants' versatility and ability to grow in high levels of contamination are easier to compare when all of the plants receive the same treatments.

Translocation is important when the remedial plan involves harvesting the shoots and leaving the roots behind, but shoot extraction amounts can be more important than translocation factors at times.

PCB concentration in the shoots of pumpkin (*C. pepo* cv Howden) occur closest to the roots and decrease as stem length increases (Zeeb et al., 2006; Whitfield Aslund et al., 2007; Whitfield Aslund et al., 2008; Low et al., 2011). The fruit of *C. pepo* cv Howden, the pumpkin, was never included in above-ground biomasses or PCB concentrations because PCBs do not migrate up the shoots in high amounts. Low et al. (2011) found that by pruning and encouragement of nodal adventitious roots doubled the amount of PCBs in the plant compared to the control pumpkin. By controlling how the plant grows and diverts its energy usage one can increase root length and density. Increasing root and shoot biomass should allow for greater accumulation to occur. After pruning and encouraging root nodal growth, a pumpkin was found to have accumulated 5,225 μg/plant, which was double the amount the pumpkin with no treatments accumulated (Low et al., 2011). Based on the current data on PCB accumulation, it would appear that pumpkin is the best candidate for phytoremediation due to its ability to grow larger, bioaccumulate more, and extract more PCBs than other plants tested and it has done so regardless of researcher and testing conditions on a consistent basis.

Measuring PCB on the basis of area planted (m^2) is beneficial because it allows researchers to determine the effects of planting densities and the time necessary to remove PCBs from soil. Pumpkin did not accumulate more PCBs than tall fescue or sedge, which was not expected due to pumpkin's biomass and its ability to concentrate PCBs within its roots. Pumpkin grew over 7 m and weigh over 4 kg (Whitfield Aslund et

al., 2007), which is much larger than the pot experiments done by Zeeb et al. (2006), where the pumpkins grew less than 30 cm weighing less than 20 g wet weight. The change in biomass could be due to the pumpkins ability to spread out while it grew and the use of fertilizer, use of a roto-tiller, and an irrigation system. It is also unclear why there were few PCBs found in the pumpkins roots (Whitfield Aslund et al., 2007). There is a possibility that since measurements were done on an area basis, the pumpkin's longer, more diffuse root systems (40–187 cm) spread beyond the area and therefore showed a low accumulation in its roots per m^2.

Tall fescue and sedge grew densely enough to accumulate more PCBs in its shoots and roots than the pumpkin. Sedge had a great difference in overall uptake and with a root system 7-16 cm long; there is a good chance this rate of accumulation could occur uniformly throughout a site, where pumpkin roots could overlap and have less nutrients and space to grow, unless there was a way to direct the roots down instead of out. The amount sedge accumulated was much more than pumpkin and tall fescue is surprising since this has not happened in other comparisons, but more reason why continuous testing is necessary to show the true consistency of the plants ability to phytoremediate soil.

Weeds appear to be able to extract equal or more PCBs than pumpkins, have a longer growing season per year, and are less affected by adverse environmental conditions. Weeds also have the advantage in that a majority of their biomass is found in their shoots, increasing the chances of better translocation factors. In several instances, weeds extracted more PCBs in the lower contaminated soil than in the higher contaminated soil. Unfortunately, it is unclear the amount of time the plants were in the

soil and the actual number of plants before applying theoretical densities. Red clover was calculated to have the highest amount extracted in its shoots, but in the supplementary data, red clover had a small concentration with a low translocation factor. Ficko et al., (2010) have been the only researchers testing accumulation rates of weeds, so more research will be necessary to determine if the plants continue to perform effectively. Future research will determine the amount of PCBs red clover and other weed species are capable of extracting in a given time frame and actual density.

Accumulation rates per m^2 were high and there was evidence that the plants are capable of retaining more PCBs without detrimental effects, means that longer planting times has promise to effectively decrease PCB soil concentrations. Soil concentrations will need to be low, but with the additional help of rhizodegradation, there is a likely chance phytoremediation can succeed. Pumpkin, squash, zucchini, tall fescue, and sedge appear to be the best PCB accumulators to date based on extracting capabilities.

Soil PCB Concentration Change

Testing soil change accounts for PCB uptake, degradation, and loss of PCBs from volatilization or blowing away. No difference was found among the plants (Table 14), however all of the plants show some promising results. The change in soil PCB concentration was converted to a per month basis to allow for better comparisons among plants. Since initial PCB soil concentration had an influence on plant uptake, it was necessary to separate the plants tested at high PCB soil concentrations from low PCB soil concentrations. Plants tested in both high and low PCB soil concentrations have large differences that could mislead the true ability by the plant to remove PCBs. For instance, the rate in which a plant removes PCBs at a low concentration does not mean that it will

remove PCBs at that rate at higher soil concentrations. Areas designated to be remediated to residential levels, <2 ppm, could benefit from phytoremediation when the initial PCB soil concentration is already low. A growing season of six months would mean that tall fescue (*Festuca arundinacea*) could be expected to decrease soil concentrations nearly 2 ppm per harvest cycle. This result does not mean that tall fescue only performs at this rate, but in a scenario of low soil concentrations, would perform at lower, but still reliable rate. It is likely that soil contaminated around 30 ppm would be depleted to industrial standards, 10-25 ppm, at a faster rate than PCB soil contaminated at 12 ppm needing to be reduced to under 2 ppm.

Plants in higher PCB contaminated soils have decreases mostly ranging from 7 to nearly 15 ppm per month. A growing season of six months could expect soil depletions of 42 to 90 ppm. Based on this information, it would appear plants could solely be used to clean up highly contaminated sites in very few harvesting cycles. However, many of these studies had unplanted controls with high changes in PCB concentrations. For instance, unplanted controls were showing PCB concentration depletions of 20 to 42 ppm after five months (Martina et al., 2009), 20 ppm after six months (Dzantor et al., 2000), 16 ppm after 100 days (Dzantor and Woolston, 2001) and 18 ppm after four months (Chekol et al., 2003). In the present analysis, the change in PCB soil concentrations for unplanted controls was accounted for by subtracting them from the planted samples. There is uncertainty if the changes in the unplanted controls were human error or from native bacteria degrading PCBs. The latter is unlikely because of the long life-span PCBs have in soil. Changes in the unplanted controls for low concentration soils did not follow the same pattern.

Tall fescue is the only plant that was used in a study measuring changes in soil concentration as well as plant concentration and uptake, which makes it difficult to determine which plant decreases PCB soil concentration at the greatest rate. Also, the studies that focused on soil changes had large concentration depletions in the unplanted controls or were done on soil with very low PCB concentrations. Sometimes the control soil showed a greater depletion than the planted soil. Tobacco does appear to reduce soil concentrations better than other plants, but more testing is needed to ensure consistency and the amount of PCBs extracted from the soil. Changes in soil PCB concentrations by cucurbits and weeds have not been researched as thoroughly as grasses and legumes. Cucurbit testing have mentioned only a slight change in soil PCB concentration (<1%), but these experiments were not working with homogenized soil (White et al., 2005; Whitfield Aslund, 2007; Whitfield Aslund, 2008). Without using homogenized soil or extensive sampling in the area the plant will grow, soil changes are going to be unobservable.

Areas where climate allows for longer growing seasons would be expected to get greater changes at the end of the growing season. Feasibility studies will show expected changes for the specific site and allow for better predictions on the length of time and harvest cycles necessary to reach remedial goals. Based on PCB concentration changes being greater in higher contaminated soil, it is likely that PCB soil concentrations will decrease at a higher rate early in the harvesting cycles than in the later due to PCB availability.

The final conclusion and statistics are limited by the number of samples available as seen by the low “n” values and high standard errors. Researchers in the field will add

to the data and show the consistency of the plants ability to uptake and degrade PCBs from soil. Future measurements should consist of shoot and root accumulation, the amount of PCBs extracted per meter squared, and soil changes. Continued field pilot testing will determine which of the plants are able to extract the most PCBs as well as have the ability to effectively decrease soil concentrations to safe levels in a reasonable amount of time.

Pumpkin (*C. pepo cv Howden*), zucchini (*C. pepo cv Senator hybrid*), tall fescue (*F. arundinacea*), sedge (*C. normalis*), Squash (*C. pepo cv Goldrush*), and tobacco (*Nicotiana tabacum*) appear to be the top candidates for phytoremediation based on PCB uptake and concentrations within the plants. The cucurbits, tall fescue, and sedge showed consistency in having higher plant concentrations accumulation rates. Weeds have great potential, but lack of research creates uncertainty. At this time, there is no concrete evidence that plants are able to decrease soil concentrations at acceptable rates and therefore more research is necessary before using them as the sole remedial strategy for an area other than for Brownfield sites and as a final step after excavation.

Regulations and Clean up Standards

There is little evidence to indicate that phytoremediation alone can clean up PCB contaminated soil unless the amount of PCBs needed to be removed is low (<10 ppm). Plants can be incorporated in the remedial process through phytostabilization before other techniques take place. Plants with a long root system such as cucurbits will work best because they will be able to pull PCBs up and store them in the roots. Tall fescue's ability to grow in soil contaminated with high PCB concentrations (4200 ppm) and then store large amounts in its roots make it a good candidate for heavily polluted soils.

Concentrating the PCBs within the roots would decrease the risk of PCBs volatilizing during construction and the root system will stabilize the ground before excavation; thereby preventing dust from being blown away and keep the soil more intact during the excavation process. While stored inside the plants, PCBs will continue to be broken down by the metabolism of the plant. It has been suggested that Brownfield sites with large volumes of soil with relatively low contamination levels may be the most appropriate market for PCB phytoremediation (Marmiroli and McCutcheon, 2003).

Barriers and biases in environmental laws and regulations favor traditional technologies over innovations such as phytoremediation (Timian and Connolly 1996). Conservative by practice, regulators, risk assessors, and design engineers naturally develop more confidence in standard practices (Marmiroli and McCutcheon, 2003). Federal laws, RCRA, and CERCLA, require the use of the BDAT for treatment and cleanup. The requirements create artificially high standards which cannot be reached with biological technologies (Timian and Connolly, 1996). As of right now, there is not sufficient evidence to establish that PCB phytoremediation alone is comparable to the best demonstrated technology (BDAT), incineration. In fact, it seems highly unlikely, regardless of efficiency, that plants will be able to remove PCBs from soil as well as and as quickly as an incinerator. However, phytoremediation will show to be cost-effective by several magnitudes, not disrupt the current soil matrix, improve animal habitats, not release contaminated dust into the air, nor will phytoremediation cause sedimentation run-off into local waterways. It is also apparent that plants do not have the capability to decrease soil concentrations by at least 90%, which is required by EPA's manual on alternative methods for PCB treatment (U.S. EPA, 1989), unless initial concentrations are

low and a reasonable amount of time is allowed. Capping and MNR are also unable to meet these expectations, but they are still used. Since capping is accepted, phytoremediation effectiveness at protecting the health and safety of humans and wildlife should be compared to capping or other accepted strategies in order to be accepted as an option. Phytoremediation can be more effective than capping and is better than MNR because it increases the rate of recovery. Over half of the 594 remedy selections from 2005-2008 consisted of no action, non-treatment, and containment methods (Figure 10). Treatment of source or groundwater consisted of the remaining 44% (U.S. EPA, 2010). Many of these sites could have benefited from the additional use of phytoremediation without costing a lot of money, however it is unclear how many of the sites dealt with groundwater or soil and whether or not PCBs were involved.

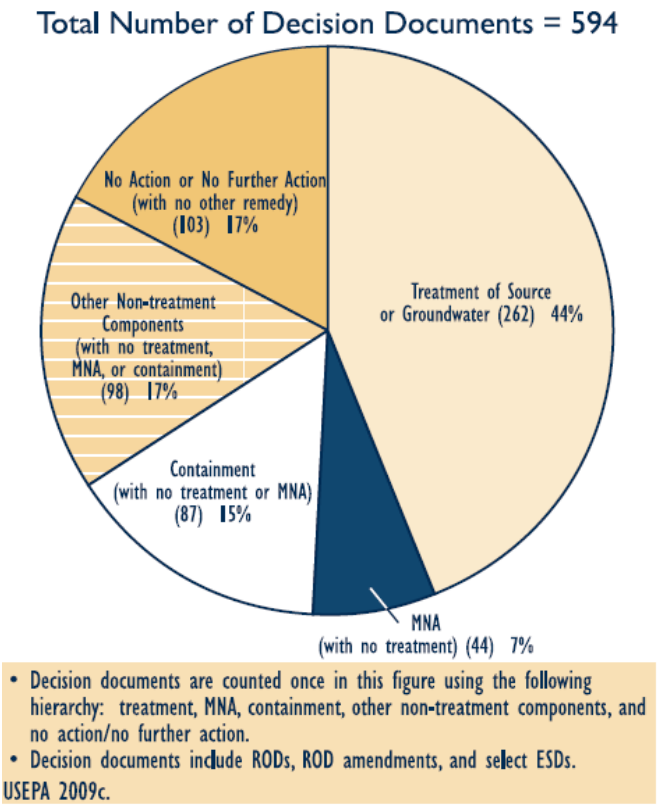


Figure 10. Remedies Selected in Decision Documents (Fiscal Year 2005-08) (EPA, 2010)

EPA has a “derived from” rule which states that any residue derived from the treatment of a listed hazardous waste must be treated as hazardous waste (40 CFR $ 261.3(c)(2)(i). A listed hazardous waste will remain a hazardous waste even after treatment (Tchobanoglous et al., 1993). The “derived from” rule requires that any hazardous waste which is treated must still be handled as if it is hazardous waste, even if bioremediation converts the hazardous material to a nonhazardous material (Timian and Connolly, 1996). Therefore, plants will need to be incinerated or placed in a hazardous waste landfill. The derived from rule will be an issue for Brownfield cleanups when plants are used for enhanced natural recovery or when plants are used after excavation takes place as a “polishing step” with no plan to remove the plants in the future.

The “contained-in” policy established contaminated media (soil) that contains a listed hazardous waste must be managed as a hazardous waste. It is not until the medium no longer “contains” a hazardous waste that it must be managed according to applicable hazardous waste management standards. Under this policy, soil deemed “clean” by the regulator may be returned to the ground without triggering RCRA Subtitle C requirements. However, full RCRA Subtitle C requirements are applicable until the contamination is removed from the medium (Schnoor, 1997). To fully adhere to the policy, all of the roots must be extracted following extraction even though PCBs are being degraded within the plant, are contained, and in some cases were going to be left in the soil (MNR and capping).

Recommendations

Policies such as the “derived from”, “contained in”, and the dilution rule, will deter people from voluntarily continuing cleanup through phytoremediation even if the

PRGs have been met. It is unclear what the protocol is for PCB contaminated soil under 50 ppm. For example, if soil is contaminated at 20 ppm, soil disposal is allowed in a municipal waste landfill, but if plants are used to lower contamination levels, they will be treated as hazardous waste due to root and possibly shoot concentrations higher than 50 ppm. Table 15 shows several superfund examples-long-term management controls and several of them have soil concentrations around 25 ppm with no further remediation conducted except capping (EPA, 1990). In one case, Wide Beach Brant, NY had a final PCB concentration of 10 ppm after excavation had taken place. No further action was done and a residential neighborhood was built. Phytoremediation could have been utilized throughout the site before, during, and after residential constructing in order to continue decreasing PCB concentrations. Therefore, the "derived from" rule and "contained in" rule should be waived in this situation because the amount of PCBs, though high in concentration, are being used on land that is not considered hazardous. These policies should be waived in other situations where translocation into the shoots does not occur and the plant is not eaten by species in the area. Since substantial time is required for a significant decrease to occur in PCB contaminated soil, the technique will best utilized in situations where time is not critical. For instance, abandoned sites could benefit from phytoremediation or they can be used as an early action plan. Any several cases, a decade of planning and negotiating over clean up standards and proposed plans occurs before any clean up takes place. Plants can therefore be used to contain PCBs and begin decreasing soil concentrations.

Table 15. Examples of Long-term Superfund Management Controls (U.S. EPA, 1990)

SUPERFUND EXAMPLES--LONG-TERM MANAGEMENT CONTROLS								
Superfund Site (ROD Date)	**Initial Source & Problem**	**Disposition**	**Initial PCB Concentration Range (ppm)**	**Final PCB Concentration (ppm)**	**Geologic/Hydrogeologic Conditions**	**Cover Design**	**Bottom Liners**	**Leachate Collection/Removal and Leak Detection**
1. Ottati and Goss, Kingston, NH (1/16/87)	! Buried drums, sludge	! Excavate ! Off-site incineration ! Cap ! Aeration ! Extract and treat groundwater	143 (soil)	20 (soil)	! Groundwater: 0-2 feet below surface ! Geology: glacial tills; bedrock	9 inches top soil	! None	Groundwater wells planned for pump and treatment
2. Re-Solve, MA North Dartmouth, MA (7/24/87)	! Waste oil spread on dirt roads ! Solvent reclamation facility	! Excavate ! Cap ! On-site treatment (dechlorination) ! Wetland restoration ! Extract and treat groundwater	15-52,000	25 (soil)	! Groundwater: 50-60 feet below surface ! Geology: sand, travel, till, bedrock	Regraded and grassed	! None	Groundwater wells planned for pump and treatment
3. Chemical Control Elizabeth, NJ (9/24/87)	! Variety of waste in drums	! In-situ location ! Debris removal ! Storm sewer repair ! Secure site (fence)	0-6	0-6	! Groundwater: 1-3 feet below surface ! Geology: sand/gravel silty sand; till; bedrock	1-3 foot gravel layer	! None ! Natural impermeable clays	None
4. Wide Beach Brant, NY (9/30/85)	! Waste oil spread on dirt roads	! Excavation ! Chemical treatment	0.05-1026	10	! Geology: silty sand/gravel; silty/clay; fractured shale	None (not feasible, a residential community)	! None	None
5. York Oil Moira, NY (2/9/89)		! Excavate ! Stabilize ! Off-site incineration ! Extract and treat groundwater	.1-210		! Groundwater: 30 feet below surface ! Geology: glacial bedrock	None (stabilization process leaves treated soils impermeable)	! None ! Natural impermeable clays	Groundwater wells planned for pump and treatment
6. Mowbray Engineering _____, AL (9/25/86)	! 3 acre swamp ! Transformer repair plant	! Close sewer ! Excavate ! Stabilize	N.D.-62 (soil)	25	! Groundwater: 18 feet below surface ! Geology: sandy; clay, rock; limestone	2 feet compacted clay, 2 feet vegetative layer, 2 feet sand, synthetic liner	! None	None
7. Pepper's Steel & Alloys Medley, FL (3/12/86)	! 30 acres trash	! Excavate ! Stabilize ! Off-site incineration ! Cap ! Extract and treat groundwater	1.5-760 (soil)	1	! Groundwater: 5-6 feet below surface ! Geology: fill; peat limestone	12 inches crushed limestone	! None	Down-gradient groundwater wells planned for pump and treatment
8. Belvidere Landfill Belvidere, IL (6/30/88)	! Landfill ! Drum Disposal	! Excavate ! Off-site incineration ! Landfill ! Cap ! Extract and treat groundwater ! Secure site	9-51,000	50	! Groundwater: 7 feet below surface ! Geology: sand; gravel; bedrock	RCRA cover	! None	Groundwater wells planned for pump and treatment
9. Fort Wayne Fort Wayne, ID (8/26/88)	! Dumping area ! Recycling plant	! Excavate ! On-site incineration ! Cap ! Contaminant wall ! Extract and treat groundwater ! Secure site	0.34-14.2	10	! Groundwater: 10-15 feet below surface ! Geology: outwash sands and gravels; lake clays, silts, and fines	2 feet clay and 6 inches vegetative layer	! None	Groundwater wells planned for pump and treatment

Rhizodegradation has been thoroughly studied with several plants. Phytoremediation should be allowed to be planted as an enhanced natural recovery method without plans for future removal in areas such as Brownfield sites since there is an unlikely chance of near-future development and if MNR is being used already. The "contained-in" policy needs to make adjustments for plants that extract PCBs from contaminated soil and in some cases used in areas not considered hazardous. The notion that all of the plant needs to be rid of PCBs is impracticable because of the ubiquitous nature of PCBs. Currently, phytoremediation has been shown to prevent mobility, be accepted by the public, and protect human health by preventing dust release. In the near future, as combinations of planting techniques, additives, and newly tested plants are researched, PCB phytoremediation will be effective in reducing PCBs to clean-up levels. Once phytoremediation has proven to be effective, it must overcome several ARARs that may be too strict to allow a slower, natural process.

EPA's green remediation policy movement should help the process of PCB phytoremediation acceptance. EPA's green remediation strategy is attempting to reduce GHG emissions along with other negative environmental impacts caused by remedial techniques by conserving natural resources, minimizing waste, and reducing energy consumption (U.S. EPA, 2008). Phytoremediation goes along with EPA's Green remediation goals by reducing the amount of energy required to remove and transport excavated soil. The removal and disposal of plant material used in phytoremediation is generally much less than typical soil extraction amounts. Therefore, phytoremediation can be a strategy for decreasing the costs of handling, processing, and possibly landfilling the materials (U.S. EPA, 2005b).The reduction of soil excavation and decreased of waste

results in less air pollutants and GHGs from heavy machinery fossil fuel consumption (U.S. EPA, 2008). Soil has an improvement in soil quality and the ecosystem is protected without destroying the local habitats. At the same time, plants are protecting the health of people and wildlife by preventing the movement of PCBs and enhancing the degradation. The money saved will allow for more sites to be remediated where there would not have been sufficient funds.

PCB phytoremediation is close to becoming an acceptable remedial technology, however further research is needed to determine if soil depletions seen in recent studies are consistent. BDAT expectations are unrealistic and comparisons between phytoremediation and other currently used remedial strategies should be used to determine if it is an acceptable option for a site. Policies regarding "derived from" and "stored in" will need to be waived or have certain exemptions in order for PCB phytoremediation benefits to outweigh current technologies. Exceptions should be allowed when soil concentrations are below hazardous levels, when monitored natural recovery (MNR) was an acceptable option, and when plants are used after construction to further PCB depletion.

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Appendix. Raw Data for Statistics.

Root Concentrations

Plant Tested	Plant type	Additive	Aroclor	Root ppm	Field/Pot Study	Initial Soil	Nat log conc	BAF	Cube root of BAF	Article
Soybean (Glycine max)	Legume	No	1260	2000	Pot	4200	7.601	0.476	0.781	Zeeb et al., 2006
Soybean (Glycine max)	Legume	No	1260	100	Pot	90	4.605	1.111	1.036	Zeeb et al., 2006
Alfalfa (Medicago sativa L.)	Legume	No	1260	53	Pot	90	3.970	0.589	0.838	Zeeb et al., 2006
Tall fescue (Festuca arundinacea)	Grass	No	1260	59	Pot	90	4.078	0.656	0.869	Zeeb et al., 2006
Tall fescue (Festuca arundinacea)	Grass	No	1260	250	Pot	250	5.521	1.000	1.000	Zeeb et al., 2006
Tall fescue (Festuca arundinacea)	Grass	No	1260	6500	Pot	4200	8.780	1.548	1.157	Zeeb et al., 2006
Sedge (Carex normalis)	Weed	No	1260	34	Pot	90	3.526	0.378	0.723	Zeeb et al., 2006
Sedge (Carex normalis)	Weed	No	1260	2200	Pot	4200	7.696	0.524	0.806	Zeeb et al., 2006
Rye grass (Lolium multiflorum)	Grass	No	1260	60	Pot	90	4.094	0.667	0.874	Zeeb et al., 2006
Reed canary grass (Phalaris arundinacea)	Grass	No	1260	46	Pot	90	3.829	0.511	0.800	Zeeb et al., 2006
Zucchini (Cucurbita pepo cv. Senator hybrid)	Cucurbit	No	1260	1600	Pot	4200	7.378	0.381	0.725	Zeeb et al., 2006
Zucchini (Cucurbita pepo cv. Senator hybrid)	Cucurbit	No	1260	290	Pot	90	5.670	3.222	1.477	Zeeb et al., 2006
Squash (Cucurbita pepo ssp. Pepo cv Goldrush)	Cucurbit	No	1260	590	Pot	250	6.380	2.360	1.331	Zeeb et al., 2006

Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1260	3200	Pot	4200	8.071	0.762	0.913	Zeeb et al., 2006
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1260	730	Pot	250	6.593	2.920	1.429	Zeeb et al., 2006
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1248	21.5	Field	6.5	3.068	3.308	1.490	Low et al., 2010
Yellow foxtail (Setaria pumila)	Weed	No	1254/1260	48	Field	31	3.871	1.548	1.157	Ficko et al., 2010
Yellow foxtail (Setaria pumila)	Weed	No	1248	3.1	Field	4.7	1.131	0.660	0.870	Ficko et al., 2010
White heath aster (Symphyotrichum ericoides)	Weed	No	1254/1260	200	Field	31	5.298	6.452	1.862	Ficko et al., 2010
Tufted vetch (Vicia cracca)	Weed	No	1254/1260	110	Field	31	4.700	3.548	1.525	Ficko et al., 2010
Tufted vetch (Vicia cracca)	Weed	No	1248	12	Field	4.7	2.485	2.553	1.367	Ficko et al., 2010
Spotted ladysthumb (Polygonum persicaria)	Weed	No	1254/1260	30	Field	31	3.401	0.968	0.989	Ficko et al., 2010
Spotted ladysthumb (Polygonum persicaria)	Weed	No	1248	15	Field	4.7	2.708	3.191	1.472	Ficko et al., 2010
Spiny sowthistle (Sonchus asper)	Weed	No	1254/1260	14	Field	31	2.639	0.452	0.767	Ficko et al., 2010
Spiny sowthistle (Sonchus asper)	Weed	No	1248	6	Field	4.7	1.792	1.277	1.085	Ficko et al., 2010
Shephard's purse (Capsella bursa-pastoris)	Weed	No	1248	24	Field	4.7	3.178	5.106	1.722	Ficko et al., 2010
Redroot pigweed (Amaranthus retroflexus)	Weed	No	1254/1260	32	Field	31	3.466	1.032	1.011	Ficko et al., 2010
Red clover (Trifolium pratense)	Weed	No	1248	8.9	Field	4.7	2.186	1.894	1.237	Ficko et al., 2010
Ragweed (Ambrosia artemisiifolia)	Weed	No	1254/1260	25	Field	31	3.219	0.806	0.931	Ficko et al., 2010

Ragweed (Ambrosia artemisiifolia)	Weed	No	1248	13	Field	4.7	2.565	2.766	1.404	Ficko et al., 2010
Queen Anne's lace (Daucus carota)	Weed	No	1254/1260	47	Field	31	3.850	1.516	1.149	Ficko et al., 2010
Queen Anne's lace (Daucus carota)	Weed	No	1248	29	Field	4.7	3.367	6.170	1.834	Ficko et al., 2010
Purple loosestrife (Lythrum salicaria)	Weed	No	1254/1260	4.7	Field	31	1.548	0.152	0.533	Ficko et al., 2010
New Englad aster (Symphyotrichum novae-angliae)	Weed	No	1254/1260	35	Field	31	3.555	1.129	1.041	Ficko et al., 2010
Lamb's quarters (Chenopodium album)	Weed	No	1248	6.2	Field	4.7	1.825	1.319	1.097	Ficko et al., 2010
Hedgemustard (Sisymbrium officinale)	Weed	No	1248	9.9	Field	4.7	2.293	2.106	1.282	Ficko et al., 2010
Garden yellowrocket (Barbarea vulgaris)	Weed	No	1248	13	Field	4.7	2.565	2.766	1.404	Ficko et al., 2010
Daisy (Chrysanthemum leucanthemum)	Weed	No	1248	5.4	Field	4.7	1.686	1.149	1.047	Ficko et al., 2010
Curly dock (Rumex crispus)	Weed	No	1248	2.5	Field	4.7	0.916	0.532	0.810	Ficko et al., 2010
Common mullein (Verbascum thapsus)	Weed	No	1248	4.8	Field	4.7	1.569	1.021	1.007	Ficko et al., 2010
Canada thistle (Cirsium arvense)	Weed	No	1254/1260	50	Field	31	3.912	1.613	1.173	Ficko et al., 2010
Canada Goldenrod (Solidago canadensis)	Weed	No	1254/1260	77	Field	31	4.344	2.484	1.354	Ficko et al., 2010
Blueweed (Echium vulgare)	Weed	No	1248	2.5	Field	4.7	0.916	0.532	0.810	Ficko et al., 2010
Blue thistle (Cirsium vulgare)	Weed	No	1254/1260	48	Field	31	3.871	1.548	1.157	Ficko et al., 2010
Blue medick (Medicago lupulina)	Weed	No	1248	17	Field	4.7	2.833	3.617	1.535	Ficko et al., 2010

Black nightshade (Solanum nigrum)	Weed	No	1248	47	Field	4.7	3.850	#####	2.154	Ficko et al., 2010
Black Mustard (Brassica nigra)	Weed	No	1254/1260	310	Field	31	5.737	#####	2.154	Ficko et al., 2010
Black bindweed (Polygonum convolvulus)	Weed	No	1248	18	Field	4.7	2.890	3.830	1.565	Ficko et al., 2010
Barnyard grass (Echinochloa crusgalli)	Grass	No	1254/1260	24	Field	31	3.178	0.774	0.918	Ficko et al., 2010
Alfalfa (Medicago sativa L.)	Legume	No		0.231	Field	0.55	-1.466	0.420	0.749	Dzantor et al., 2000
Alfalfa (Medicago sativa L.)	Legume	Yes		0.268	Pot	0.55	-1.318	0.487	0.787	Dzantor et al., 2000
Alfalfa (Medicago sativa L.)	Legume	Yes		0.325	Field	0.55	-1.125	0.590	0.839	Dzantor et al., 2000
Alfalfa (Medicago sativa L.)	Legume	Yes		0.326	Field	0.55	-1.121	0.593	0.840	Dzantor et al., 2000
white lupin (Lupinus albus)	Legume	No	1268	19	Field	105	2.944	0.181	0.566	White et al., 2005
Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	No	1268	85	Pot	105	4.443	0.810	0.932	White et al., 2005
Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	No	1268	200	Field	105	5.298	1.905	1.240	White et al., 2005
Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	Yes	1268	400	Field	105	5.991	3.810	1.562	White et al., 2005
Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	Yes	1268	405	Field	105	6.004	3.857	1.568	White et al., 2005
Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	No	1268	440	Pot	105	6.087	4.190	1.612	White et al., 2005
Summer Squash (Cucurbita pepo ssp ovifera cv Zephyr)	Cucurbit	No	1268	50	Pot	105	3.912	0.476	0.781	White et al., 2005
Summer Squash (Cucurbita pepo ssp ovifera cv Zephyr)	Cucurbit	No	1268	275	Pot	105	5.617	2.619	1.378	White et al., 2005

Summer Squash (Cucurbita pepo ssp ovifera cv Zephyr)	Cucurbit	Yes	1268	390	Pot	105	5.966	3.714	1.549	White et al., 2005
Summer Squash (Cucurbita pepo ssp ovifera cv Zephyr)	Cucurbit	Yes	1268	410	Pot	105	6.016	3.905	1.575	White et al., 2005
Squash (Cucurbita pepo ssp. Pepo cv Goldrush)	Cucurbit	No	1268	75	Field	105	4.317	0.714	0.894	White et al., 2005
Cucumber (Cucumis sativus cv Marketmore)	Cucurbit	No	1268	100	Field	105	4.605	0.952	0.984	White et al., 2005
Cucumber (Cucumis sativus cv Marketmore)	Cucurbit	No	1268	225	Pot	105	5.416	2.143	1.289	White et al., 2005
Cucumber (Cucumis sativus cv Marketmore)	Cucurbit	Yes	1268	315	Pot	105	5.753	3.000	1.442	White et al., 2005
Cucumber (Cucumis sativus cv Marketmore)	Cucurbit	Yes	1268	375	Pot	105	5.927	3.571	1.529	White et al., 2005
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1254/1260	50	Field	21	3.912	2.381	1.335	Whitfield Aslund et al., 2008
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No		60	Field	21	4.094	2.857	1.419	Whitfield Aslund et al., 2008
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No		78	Field	21	4.357	3.714	1.549	Whitfield Aslund et al., 2008
Tall fescue (Festuca arundinacea)	Grass	No	1254/1260	15	Field	45	2.708	0.333	0.693	Whitfield Aslund et al., 2007
Sedge (Carex normalis)	Weed	No	1254/1260	66	Field	45	4.190	1.467	1.136	Whitfield Aslund et al., 2007
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1254/1260	40	Field	45	3.689	0.889	0.961	Whitfield Aslund et al., 2007
Alfalfa (Medicago sativa L.)	Legume	No		0.115	Field	0.45	-2.163	0.256	0.635	Xu et al., 2010
Alfalfa (Medicago sativa L.)	Legume	Yes		0.142	Field	0.45	-1.950	0.316	0.681	Xu et al., 2010

Shoot Concentrations

Plant Tested	Plant Group	Additive	Aroclor	Shoot ppm	Field/Pot Study	Initial Soil	Natural Log Shoot ppm	Shoot BAF	Cube-root BAF	Article
Alfalfa (Medicago sativa L.)	Legume	No	missing	0.0033	Field	0.45	-5.71383	0.0073	0.085635	Xu et al., 2010
Alfalfa (Medicago sativa L.)	Legume	Yes		0.0267	Field	0.45	-3.62309	0.0593	0.243584	Xu et al., 2010
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1254/1260	6.7	Field	45	1.902108	0.1489	0.385861	Whitfield Aslund et al., 2007
Tall fescue (Festuca arundinacea)	Grass	No	1254/1260	4.7	Field	45	1.547563	0.1044	0.323179	Whitfield Aslund et al., 2007
Sedge (Carex normalis)	Weed	No	1254/1260	13	Field	45	2.564949	0.2889	0.537484	Whitfield Aslund et al., 2007
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1254/1260	11	Field	21	2.397895	0.5238	0.723747	Whitfield Aslund et al., 2008
Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	No	1268	15	Field	105	2.70805	0.1429	0.377964	White et al., 2005
Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	Yes	1268	50	Field	105	3.912023	0.4762	0.690066	White et al., 2005
Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	Yes	1268	25	Field	105	3.218876	0.2381	0.48795	White et al., 2005

Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	No	1268	22	Pot	105	3.091042	0.2095	0.457738	White et al., 2005
Zuchini (Cucurbita pepo ssp pepo cv Black Beauty)	Cucurbit	No	1268	16	Pot	105	2.772589	0.1524	0.39036	White et al., 2005
Summer Squash (Cucurbita pepo ssp ovifera cv Zephyr)	Cucurbit	No	1268	5	Pot	105	1.609438	0.0476	0.218218	White et al., 2005
Summer Squash (Cucurbita pepo ssp ovifera cv Zephyr)	Cucurbit	Yes	1268	25	Pot	105	3.218876	0.2381	0.48795	White et al., 2005
Summer Squash (Cucurbita pepo ssp ovifera cv Zephyr)	Cucurbit	Yes	1268	25	Pot	105	3.218876	0.2381	0.48795	White et al., 2005
Summer Squash (Cucurbita pepo ssp ovifera cv Zephyr)	Cucurbit	No	1268	10	Pot	105	2.302585	0.0952	0.308607	White et al., 2005
Squash (Cucurbita pepo ssp. Pepo cv Goldrush)	Cucurbit	No	1268	10	Field	105	2.302585	0.0952	0.308607	White et al., 2005
Cucumber (Cucumis sativus cv Marketmore)	Cucurbit	No	1268	10	Pot	105	2.302585	0.0952	0.308607	White et al., 2005
Cucumber (Cucumis sativus cv Marketmore)	Cucurbit	Yes	1268	35	Pot	105	3.555348	0.3333	0.57735	White et al., 2005
Cucumber (Cucumis sativus cv Marketmore)	Cucurbit	Yes	1268	10	Pot	105	2.302585	0.0952	0.308607	White et al., 2005
Cucumber (Cucumis sativus cv Marketmore)	Cucurbit	No	1268	5	Field	105	1.609438	0.0476	0.218218	White et al., 2005
White lupin (Lupinus albus)	Legume	No	1268	8	Field	105	2.079442	0.0762	0.276026	White et al., 2005
Alfalfa (Medicago sativa L.)	Legume	No		0.0274	Field	0.55	-3.59721	0.0498	0.2232	Teng et al., 2010

Alfalfa (Medicago sativa L.)	Legume	Yes		0.0366	Field	0.55	-3.30771	0.0665	0.257964	Teng et al., 2010
Alfalfa (Medicago sativa L.)	Legume	Yes		0.0421	Field	0.55	-3.16771	0.0765	0.276668	Teng et al., 2010
Alfalfa (Medicago sativa L.)	Legume	Yes		0.04969	Pot	0.55	-3.00195	0.0903	0.300575	Teng et al., 2010
Yellow rocket mustard (Barbarea vulgaris)	Weed	No	1248	1.1	Field	4.7	0.489561	0.234	0.483779	Ficko et al., 2010
Yellow foxtail (Setaria pumila)	Weed	No	1248	0.37	Field	4.7	-0.98083	0.0787	0.280577	Ficko et al., 2010
Yellow foxtail (Setaria pumila)	Weed	No	1254/1260	2.6	Field	31	-0.05403	0.0839	0.289605	Ficko et al., 2010
Wild carrot (Daucus carota)	Weed	No	1248	3.7	Field	4.7	1.381081	0.7872	0.887262	Ficko et al., 2010
Wild carrot (Daucus carota)	Weed	No	1254/1260	21	Field	31	2.302585	0.6774	0.823055	Ficko et al., 2010
Tufted betch (Vicia cracca)	Weed	No	1254/1260	35	Field	31	3.475686	1.129	1.062559	Ficko et al., 2010
Tufted betch (Vicia cracca)	Weed	No	1248	0.64	Field	4.7	-0.4943	0.1362	0.369012	Ficko et al., 2010
Sow thistle (Sonchus asper)	Weed	No	1254/1260	5.8	Field	31	1.768866	0.1871	0.432547	Ficko et al., 2010
Sow thistle (Sonchus asper)	Weed	No	1248	1.7	Field	4.7	0.305645	0.3617	0.601417	Ficko et al., 2010
Shepherd's purse (Capsella bursa-pastoris)	Weed	No	1248	2.3	Field	4.7	0.916291	0.4894	0.699544	Ficko et al., 2010
Redroot pigweed (Amaranthus retroflexus)	Weed	No	1254/1260	5.7	Field	31	0.725033	0.1839	0.428802	Ficko et al., 2010
Red clover (Trifolium pratensea)	Weed	No	1248	0.6	Field	4.7	-0.59784	0.1277	0.357295	Ficko et al., 2010
Ragweed (Ambrosia artemisiifolia)	Weed	No	1248	1.3	Field	4.7	-0.60752	0.2766	0.525924	Ficko et al., 2010

Ragweed (Ambrosia artemisiifolia)	Weed	No	1254/1260	3.6	Field	31	1.277818	0.1161	0.340777	Ficko et al., 2010
Purple loosestrife (Lythrum salicaria)	Weed	No	1254/1260	5.7	Field	31	0.978326	0.1839	0.428802	Ficko et al., 2010
New England aster (Symphyotrichum novae-angliae)	Weed	No	1254/1260	2.4	Field	31	0.939421	0.0774	0.278243	Ficko et al., 2010
Mullein (Verbascum thapsus)	Weed	No	1248	0.87	Field	4.7	-0.44177	0.1851	0.43024	Ficko et al., 2010
Lamb's quarters (Chenopodium album)	Weed	No	1248	0.42	Field	4.7	-0.8675	0.0894	0.298934	Ficko et al., 2010
Ladysthumb (Polygonum persicaria)	Weed	No	1254/1260	2.3	Field	31	0.086178	0.0742	0.272385	Ficko et al., 2010
Ladysthumb (Polygonum persicaria)	Weed	No	1248	4.8	Field	4.7	1.321756	1.0213	1.010582	Ficko et al., 2010
Hedge mustard (Sisymbrium officinale)	Weed	No	1248	1.3	Field	4.7	-0.00381	0.2766	0.525924	Ficko et al., 2010
Heath aster (Symphyotrichum ericoides)	Weed	No	1254/1260	17	Field	31	2.723799	0.5484	0.740532	Ficko et al., 2010
Goldenrod (Solidago canadensis)	Weed	No	1254/1260	8.3	Field	31	1.929345	0.2677	0.517438	Ficko et al., 2010
Daisy (Chrysanthemum leucanthemum)	Weed	No	1248	3.5	Field	4.7	0.916291	0.7447	0.862949	Ficko et al., 2010
Curly dock (Rumex crispus)	Weed	No	1248	1.5	Field	4.7	0.3975	0.3191	0.564933	Ficko et al., 2010
Canada thistle (Cirsium arvense)	Weed	No	1254/1260	2.9	Field	31	2.640142	0.0935	0.305857	Ficko et al., 2010
Bull thistle (Cirsium vulgare)	Weed	No	1254/1260	2.5	Field	31	0.310935	0.0806	0.283981	Ficko et al., 2010
Blueweed (Echium vulgare)	Weed	No	1248	2.1	Field	4.7	-0.05129	0.4468	0.668437	Ficko et al., 2010
Black nightshade (Solanum nigrum)	Weed	No	1248	3.6	Field	4.7	-0.05446	0.766	0.87519	Ficko et al., 2010

Black Mustard (Brassica nigra)	Weed	No	1254/1260	13	Field	31	0.405465	0.4194	0.647576	Ficko et al., 2010
Black medick (Medicago Lupulina)	Weed	No	1248	3.5	Field	4.7	1.484283	0.7447	0.862949	Ficko et al., 2010
Black bindweed (Polygonum convolvulus)	Weed	No	1248	1.2	Field	4.7	0.210747	0.2553	0.505291	Ficko et al., 2010
Barnyard grass (Echinochloa crusgalli)	Grass	No	1254/1260	2.5	Field	31	1.121743	0.0806	0.283981	Ficko et al., 2010
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1248	3.5	Field	6.5	1.252763	0.5385	0.733799	Low et al., 2010
Zucchini (Cucurbita pepo cv. Senator hybrid)	Cucurbit	No	1260	11	Pot	90	2.397895	0.1222	0.349603	Zeeb et al., 2006
Zucchini (Cucurbita pepo cv. Senator hybrid)	Cucurbit	No	1260	30	Pot	4200	3.401197	0.0071	0.084515	Zeeb et al., 2006
Squash (Cucurbita pepo ssp. Pepo cv Goldrush)	Cucurbit	No	1260	13	Pot	250	2.564949	0.052	0.228035	Zeeb et al., 2006
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1260	14	Pot	250	2.639057	0.056	0.236643	Zeeb et al., 2006
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	No	1260	84	Pot	4200	4.430817	0.02	0.141421	Zeeb et al., 2006
Tall fescue (Festuca arundinacea)	Grass	No	1260	1.7	Pot	90	0.530628	0.0189	0.137437	Zeeb et al., 2006
Tall fescue (Festuca arundinacea)	Grass	No	1260	8.6	Pot	250	2.151762	0.0344	0.185472	Zeeb et al., 2006
Tall fescue (Festuca arundinacea)	Grass	No	1260	98	Pot	4200	4.584967	0.0233	0.152753	Zeeb et al., 2006
Sedge (Carex normalis)	Weed	No	1260	19	Pot	90	2.944439	0.2111	0.459468	Zeeb et al., 2006
Sedge (Carex normalis)	Weed	No	1260	470	Pot	4200	6.152733	0.1119	0.334522	Zeeb et al., 2006
Rye grass (Lolium multiflorum)	Grass	No	1260	1.3	Pot	90	0.262364	0.0144	0.120185	Zeeb et al., 2006
Reed canary grass (Phalaris arundinacea)	Grass	No	1260	1.1	Pot	90	0.09531	0.0122	0.110554	Zeeb et al., 2006

Soybean (Glycine max)	Legume	No	1260	0.32	Pot	90	-1.13943	0.0036	0.059628	Zeeb et al., 2006
Soybean (Glycine max)	Legume	No	1260	3.4	Pot	4200	1.223775	0.0008	0.028452	Zeeb et al., 2006
Alfalfa (Medicago sativa L.)	Legume	No	1260	1.2	Pot	90	0.182322	0.0133	0.11547	Zeeb et al., 2006

Plant and Shoot Uptake

Plant Tested	Plant Group	Arocl or	Initial Soil (ppm)	Additive	micrograms/ mo (shoot)	micrograms/m o (plant)	micrograms (roots)	microgram(shoot)	Field/Pot Study	Natural Log shoot upt	Natural log plant upt	Reference
Alfalfa (Medicago sativa L.)	Legume		0.45	No	0.01	0.04	0.12	0.02	Field	-5.203	-3.127	Xu et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.45	Yes	0.20	0.53	1.00	0.59	Field	-1.630	-0.639	Xu et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.55	No	0.62	4.81	25.16	3.70	Field	-0.484	1.571	Teng et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.55	Yes	0.91	6.97	36.34	5.45	Field	-0.096	1.941	Teng et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.55	Yes	1.69	10.17	50.87	10.15	Field	0.525	2.319	Teng et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.55	Yes	2.08	9.58	44.99	12.48	Field	0.732	2.259	Teng et al., 2010
Tall fescue (Festuca arundinacea)	Grass	1260	90	No	2.85	17.85	30.00	5.70	Pot	1.047	2.882	Zeeb et al., 2006
Tall fescue (Festuca arundinacea)	Grass	1260	250	No	11.50	146.50	270.00	23.00	Pot	2.442	4.987	Zeeb et al., 2006
Tall fescue (Festuca arundinacea)	Grass	1260	4200	No	75.00	2925.00	5700.00	150.00	Pot	4.317	7.981	Zeeb et al., 2006

Soybean (Glycine max)	Legume	1260	90	No	0.85	32.35	63.00	1.70	Pot	-0.163	3.477	Zeeb et al., 2006
Soybean (Glycine max)	Legume	1260	4200	No	6.00	401.00	790.00	12.00	Pot	1.792	5.994	Zeeb et al., 2006
Alfalfa (Medicago sativa L.)	Legume	1260	90	No	2.20	18.70	33.00	4.40	Pot	0.788	2.929	Zeeb et al., 2006
Reed canary grass (Phalaris arundinacea)	Grass	1260	90	No	2.30	21.80	39.00	4.60	Pot	0.833	3.082	Zeeb et al., 2006
Rye grass (Lolium multiflorum)	Grass	1260	90	No	1.65	18.15	33.00	3.30	Pot	0.501	2.899	Zeeb et al., 2006
Sedge (Carex normalis)	Weed	1260	90	No	30.50	41.00	21.00	61.00	Pot	3.418	3.714	Zeeb et al., 2006
Sedge (Carex normalis)	Weed	1260	4200	No	30.00	100.00	140.00	60.00	Pot	3.401	4.605	Zeeb et al., 2006
Squash (Cucurbita pepo ssp. Pepo cv Goldrush)	Cucurbit	1260	250	No	27.50	127.50	200.00	55.00	Pot	3.314	4.848	Zeeb et al., 2006
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	1260	250	No	30.00	175.00	290.00	60.00	Pot	3.401	5.165	Zeeb et al., 2006
Pumpkin (Cucurbita pepo cv.	Cucurbit	1260	4200	No	145.00	275.00	260.00	290.00	Pot	4.977	5.617	Zeeb et al., 2006

Howden)												
Zucchini (Cucurbita pepo cv. Senator hybrid)	Cucurbit	1260	90	No	32.50	138.00	211.00	65.00	Pot	3.481	4.927	Zeeb et al., 2006
Zucchini (Cucurbita pepo cv. Senator hybrid)	Cucurbit	1260	4200	No	24.50	75.50	102.00	49.00	Pot	3.199	4.324	Zeeb et al., 2006
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	1248	5.6	No		842.40			Field		6.736	Low et al., 2011
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	1248	5.6	No		1115.92			Field		7.017	Low et al., 2011
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	1248	5.6	Yes		1694.48			Field		7.435	Low et al., 2011
Pumpkin (Cucurbita pepo cv. Howden)	Cucurbit	1248	5.6	Yes		2089.80					7.645	Low et al., 2011

Soil change for low initial soil concentrations

Plant Tested	Plant Group	Aroclor	Initial Soil (ppm)	Field/Pot Study	Soil change rate (conc change ppm/month) Adjusted control	Additive	Reference
Alfalfa (Medicago sativa L.)	Legume		0.456	Field	0.046666667	Yes	Xu et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.456	Field	0.056666667	No	Xu et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.55	Field	0.04	Yes	Teng et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.55	Field	0.06	Yes	Teng et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.55	Field	0.16	Yes	Teng et al., 2010
Alfalfa (Medicago sativa L.)	Legume		0.55	Field	0.215	Yes	Teng et al., 2010
Alfalfa (Medicago sativa L.)	Legume		4.52	Pot	0.2175	No	Chen et al., 2009
Alfalfa (Medicago sativa L.)	Legume		4.52	Pot	0.308475	Yes	Chen et al., 2009
Alfalfa (Medicago sativa L.)	Legume		0.33	Pot	0.09	No	Chen et al., 2005
Alfalfa (Medicago sativa L.)	Legume		0.33	Pot	0.2	Yes	Chen et al., 2005
Alfalfa (Medicago sativa L.)	Legume		0.33	Pot	0.08	Yes	Chen et al., 2005
Alfalfa (Medicago sativa L.)	Legume		0.33	Pot	0.23	Yes	Chen et al., 2005
Rice (Oryza sativa)	Crop		4.52	Pot	0.2226	No	Chen et al., 2009
Rice (Oryza sativa)	Crop		4.52	Pot	0.305	Yes	Chen et al., 2009
Ryegrass (Lolium perenne L)	Grass		4.52	Pot	0.2395	No	Chen et al., 2009
Ryegrass (Lolium perenne L)	Grass		4.52	Pot	0.27225	Yes	Chen et al., 2009
Tall fescue (Festuca arundinacea)	Grass		4.52	Pot	0.20675	No	Chen et al., 2009
Tall fescue (Festuca arundinacea)	Grass		4.52	Pot	0.46	Yes	Chen et al., 2009

Soil change for high initial soil concentrations

Plant Tested	Plant Group	Aroclor	Initial Soil (ppm)	Field/Pot Study	Soil change rate (conc change ppm/month) Adjusted control	Additive	Reference
Harseradish (Armoracia rusticana)	Crop	1248/1260	172	Pot	4.20	No	Martina et al., 2009
Black nightshade (Solanum nigrum)	Weed	1248/1260	221	Pot	0.80	No	Martina et al., 2009
Harseradish (Armoracia rusticana)	Crop	1248/1260	239	Pot	5.30	No	Martina et al., 2009
Tobacco (Nicotiana tabacum)	Crop	1248/1260	330	Pot	17.60	No	Martina et al., 2009
Black nightshade (Solanum nigrum)	Weed	1248/1260	345	Pot	13.20	No	Martina et al., 2009
Tobacco (Nicotiana tabacum)	Crop	1248/1260	348	Pot	12.90	No	Martina et al., 2009
Alfalfa (Medicago sativa L.)	Legume	1248/1260	361	Pot	8.40	No	Martina et al., 2009
Tobacco (Nicotiana tabacum)	Crop	1248/1260	470	Field	14.00	No	Martina et al., 2009
Black nightshade (Solanum nigrum)	Weed	1248/1260	470	Field	12.20	No	Martina et al., 2009
Alfalfa (Medicago sativa L.)	Legume	1248/1260	470	Field	6.00	No	Martina et al., 2009
Deertongue (Panicum clandestinum)	Grass	1248	100	Pot	13.50	No	Chekol et al., 2003
Reed canarygrass (Phalaris arundinacea)	Grass	1248	100	Pot	13.75	No	Chekol et al., 2003
Switchgrass (Panicum virgatum)	Grass	1248	100	Pot	12.75	No	Chekol et al., 2003
Tall fescue (Festuca arundinacea)	Grass	1248	100	Pot	12.25	No	Chekol et al., 2003
Flatpea (Lathyrus sylvestris)	Legume	1248	100	Pot	13.50	No	Chekol et al., 2003
Sericea lespedeza (Lespedeza cuneata)	Legume	1248	100	Pot	13.25	No	Chekol et al., 2003
Alfalfa (Medicago sativa L.)	Legume	1248	100	Pot	14.75	No	Chekol et al., 2003
Deertongue (Panicum clandestinum)	Grass	1248	100	Pot	1.67	No	Dzantor et al., 2000
Reed canarygrass (Phalaris arundinacea)	Grass	1248	100	Pot	6.50	No	Dzantor et al., 2000
Switchgrass (Panicum virgatum)	Grass	1248	100	Pot	5.33	No	Dzantor et al., 2000

Tall fescue (Festuca arundinacea)	Grass	1248	100	Pot	2.00	No	Dzantor et al., 2000
Flatpea (Lathyrus sylvestris)	Legume	1248	100	Pot	4.83	No	Dzantor et al., 2000
Sericea lespedeza (Lespedeza cuneata)	Legume	1248	100	Pot	2.60	No	Dzantor et al., 2000
Tobacco (Nicotiana tabacum)	Crop	1242	164	Field	5.70	No	Gichner et al., 2007
Tobacco (Nicotiana tabacum)	Crop	1242	164	Field	21.60	Yes	Gichner et al., 2007
Tobacco (Nicotiana tabacum)	Crop	1242	265	Field	16.10	No	Gichner et al., 2007
Flatpea (Lathyrus sylvestris)	Legume	1248	50	Pot	1.10	Yes	Dzantor and Woolston, 2001
Reed canarygrass (Phalaris arundinacea)	Grass	1248	50	Pot	1.42	No	Dzantor and Woolston, 2001
Reed canarygrass (Phalaris arundinacea)	Grass	1248	50	Pot	1.50	Yes	Dzantor and Woolston, 2001
Reed canarygrass (Phalaris arundinacea)	Grass	1248	50	Pot	0.30	Yes	Dzantor and Woolston, 2001
Reed canarygrass (Phalaris arundinacea)	Grass	1248	50	Pot	0.61	Yes	Dzantor and Woolston, 2001
Burr medic (Medicago polymorpha)	Legume	1248	50	Pot	2.10	No	Dzantor and Woolston, 2001